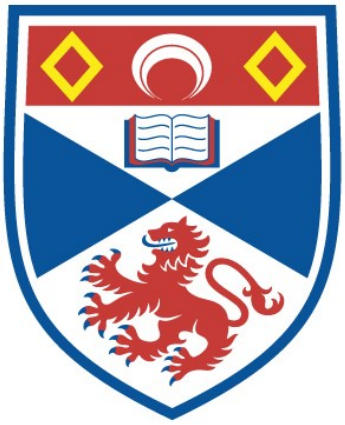
EUTROPHICATION OF LOCH KILCONQUHAR, WITH SPECIAL REFERENCE TO PHOSPHATE

Mashhor Mansor

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews



1982

3rd Copy

EUTROPHICATION OF LOCH KILCONQUHAR, WITH SPECIAL REFERENCE TO PHOSPHATE

by

Mashhor Mansor

A thesis submitted to the
University of St. Andrews
for the Degree of
Doctor of Philosophy.

Department of Botany,
St. Salvator's College,
University of St. Andrews.

October 1981

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

ABSTRACT

This thesis is mainly based on work done in Loch Kilconquhar, Fife, and also to a lesser extent in Loch Lindores, Fife, from March 1979 to March 1981. It discusses the seasonal productivity of the lakes and also the nutrient concentrations, with special reference to phosphate.

The overall productivity of phytoplankton in Loch Kilconquhar is high compared with Loch Lindores. The high plankton densities in Loch Kilconquhar during winter were attributed to Diatom species such as Stephanodiscus. Anabaena flos-aquae formed the massive bloom during May 1980 and reached the maximum value of 461.84 ± 47.02 mg m^{-2} chlorophyll a in the middle of the month, which was followed by a second blue-green bloom of Aphanizomenon flos-aquae in late summer.

The submerged macrophytes such as Myriophyllum spicatum, Zanichellia palustris and Enteromorpha intestinalis grew well on the west side of the loch after the decline of the Anabaena bloom in July 1980. The value of sedimentary chlorophyll reached a maximum of 13.96 ± 2.04 mg m^{-2} in late April 1980.

The high concentration of Soluble Reactive Phosphate (range: 0.004 - 0.780 mg/l PO_4-P) and Nitrate-nitrogen (range: 0.980 - 2.350 mg/l NO_3-N) also indicates that Loch Kilconquhar is a nutrient-rich freshwater loch. It is interesting to note that the soluble phosphate is exceptionally high compared with other freshwater lochs in Scotland. There are several possible reasons for this high concentration. Firstly, drainage from an agricultural area may contain much phosphate. However, the inflow in this case has little

soluble phosphate but is high in soluble nitrate. Secondly, decomposition of organisms, notably phytoplankton blooms and macrophytes, may contribute to the high concentration of phosphate; these organisms, however, must in turn obtain their phosphorus from water and sediment.

The third possibility, and probably the most important, is the nutrient release from the loch sediment. In a laboratory experiment, it was shown that when the dissolved oxygen dropped below 1 mg/l and the redox potential E_7 fell below 240 mVolt, substantial amounts of nutrients, particularly phosphate, were released into the overlying water.

The primary source of nutrient in Loch Kilconquhar is the phosphorus-rich excrements of the large wildfowl population and also gulls on the loch. The results show that one g of fresh duck dropping has a mean content of 4170 ± 350 mg/kg total phosphate and one g of gull dropping has 5072 ± 748 mg/kg total phosphate.

DECLARATION

I hereby declare that this thesis is of my own composition, that it is based on an accurate record of work carried out by me, and that it has not been previously presented in application for a higher degree.

Mashhor Mansor

St. Andrews, October 1981.

CERTIFICATE

I certify that Mashhor Mansor has spent twelve terms of research under my direction, that he has fulfilled the conditions of Ordinance General No. 12 and Resolution of the University Court 1967 No. 1, and that he is qualified to submit the accompanying thesis in application for the degree of Doctor of Philosophy.

D.H.N. Spence

St. Andrews, October 1981.

ACKNOWLEDGEMENTS

I am highly indebted to Professor D.H.N. Spence for supervising the work presented in this thesis, and for his continued interest and guidance throughout my studies.

I wish to express my thanks to Mr. R.B. Stephenson and Mr. D. Forbes for their help in the field works. Thanks are also due to my friends in St. Andrews, especially to Stephen Maberly, Patricia Chambers, John Glowa, Abdul Matin, Vinum Chiapanich, Manaf Ali and Khalid, for their valuable suggestions in times of need.

I also wish to thank my parents, my wife and my son for encouraging and inspiring me in my work.

Finally, I gratefully acknowledge the University Science Malaysia for awarding the fellowship and also the Government of Malaysia for giving me this opportunity for higher studies.

CONTENTS

INTRODUCTION

INTRODUCTION

According to Franke (1975), man's close dependence on the presence of water is well-documented. Many of the great past civilizations were born and evolved because of the presence of an adequate water supply for drinking, food preparation, commercial communication and irrigation. The Nile in Egypt, the Tigris and Euphrates in Mesopotamia, the Yellow River in China and the Indus in India, have all been sites of significant civilizations.

We are almost unaware that our own existence is still dependent on water and that the world's supply of clean water, so essential to our life, may well be depleted and exhausted in the near future. It should be noted that the problem of maintaining an adequate and pure water supply is no longer a minor issue, but a global problem which faces all the nations in the world.

The problems of pollution and eutrophication of freshwater terms defined presently are well-known to be crucial, particularly for industrial countries with high population density. According to Ravera (1978), an increase in the consumption of freshwater and a decrease in the quantity of clean water available could have very serious consequences in certain areas.

As explained by Vollenweider (1970) it is virtually impossible to make a clear-cut distinction between water pollution and eutrophication, as they are interrelated. To a certain extent, however, a line may be drawn. In the case of pollution, the pollutant sources are usually readily

identified (for example, factory discharge) and the toxic effects on the aquatic ecosystem are immediate. With eutrophication, on the other hand, the effects are gradual and the sources are sometimes difficult to detect without much study (for example, involving inflow, lake sediment or even dense waterfowl population).

Downey (1977) and Palmer (1980) refer to "eutrophication" as the continuous enrichment of water by the addition of substances such as phosphate and nitrate that provide for the increasing growth of aquatic life, particularly unwanted algae. Subsequently, serious oxygen depletion can occur, particularly at night, resulting in marked deterioration in water quality. Eutrophication implies instability or change.

Nowadays, the rate of eutrophication is greatly accelerated by the activities of man in discharging excessive nutrients to the water. Vallentyne (1974) calls this process "cultural" or "man-made" eutrophication. As stated before, this more rapid process has been taking place in thousands of lakes in recent decades, particularly in the developed countries like U.S.A., Britain and Japan.

Hasler and Ingersoll (1970) stressed "cultural" in the sense that it speeds up a natural phenomenon through municipal sewage, industrial waste and agricultural run-off. It has been further claimed by Vallentyne (1974) that at least 50% of phosphate in municipal sewage in North America is derived from detergents which employed phosphate (example: sodium triphosphate) as an ingredient to combat water hardness. As a result, Gregor and Johnson (1979) observed that more than one third of America's 100,000 lakes are showing signs of

cultural eutrophication.

According to Golterman (1977) most lakes in Europe including those in lowland Britain, are also seriously threatened by cultural eutrophication. Ward and Dubos (1980) stated that Britain is one of the most highly fertilized farming countries in the world; only Japan and the Netherlands use artificial fertilizers more intensively. Every year British farmers apply at least three times more nitrogen per acre than the Americans. The Royal Commission on Environmental Pollution concluded in its first report that in conditions of good husbandry, run-off is still not a major problem. However, there is an alarming consequence of nitrogen run-off when the high accumulation of nitrate in drinking water, approximately 11 mg/l $[NO_3\text{-}N]$ or more, becomes toxic nitrite when consumed by humans.

Armitage (1974) grouped both manufactured chemicals and animal manures as fertilizers, since their soluble products are taken up by the plant in a more or less identical manner. Paulik (1971) stated that the finest natural fertilizer is from the colonies of guano birds, notably cormorant, gannet and pelican, normally found on the islands of Peru's coastal desert strips. However Pelikan, Hadec and Stastray (1978) pointed out that waterfowl excrements can eutrophicate a lake and Leentvaar (1966) further added that a number of lakes in bird reserves and sanctuaries are rapidly becoming over-eutrophicated. In this particular case, the rate of natural eutrophication is speeded up by bird droppings and is comparable to cultural eutrophication.

Phosphate and nitrate are the most important nutrients

in eutrophication. According to Hutchinson (1975) and Gymer (1973), phosphate ion PO_4^{-3}, and nitrate ion NO_3^- are the forms in which these elements are most generally assimilated by living organisms such as phytoplankton, particularly in fresh water lakes. In this thesis, therefore, these elements are estimated as soluble phosphate phosphorus (PO_4-P) and nitrate-nitrogen (NO_3-N). Golterman (1977) stated that nutrient poor lakes generally have less phosphate than nitrate and that phosphate concentration in a nutrient rich lake is generally high.

A study of macrophytes of Scottish lochs by Spence (1964) included Loch Lindores and Loch Kilconquhar. He indicated that these two lochs were typical lowland lochs which showed signs of eutrophication.

This thesis is particularly concerned with the cultural and natural eutrophication of two Scottish lochs, Loch Lindores and Loch Kilconquhar. In the case of Loch Lindores, the likely sources of nutrients were held to result from cultural eutrophication, artificial and natural fertilizers leached from farmland. On the other hand, Loch Kilconquhar may be affected not only by agricultural sources, but also by biological sources, such as bird droppings. That is, both cultural and very rapid natural eutrophication may be occurring in Loch Kilconquhar.

The first chapter consists mainly of a comparative study between these two eutrophic lochs. In the event, Loch Kilconquhar was found to be more eutrophicated than Loch Lindores, so the second chapter is devoted to this loch, particularly to the sources of its nutrients.

Chapter 3 constitutes the fundamental processes that regulate nutrient supply and particularly nutrient release from Loch Kilconquhar sediments. Results of laboratory studies of redox potential in relation to phosphate release from these sediments are also discussed and the chapter concludes with a general discussion.

CHAPTER I

A COMPARATIVE STUDY BETWEEN LOCH LINDORES AND LOCH KILCONQUHAR

I .1) AIMS AND METHODS

To initiate this comparative study, a number of biological and environmental features were measured over a two year period. These included seasonal changes in water chemistry, particularly the soluble phosphate and soluble nitrate concentrations in which such factors are likely to govern the phytoplankton crop densities.

Apart from this, the dissolved oxygen (DO) concentration, pH, conductivity, alkalinity, light intensity, sediment chemistry, sedimentary chlorophyll and submerged macrophytes were also studied.

Both the selected lochs are typically lowland lochs which are situated in agricultural belts, in Fife Region, South East Scotland. Since Loch Lindores is almost surrounded by arable land, the influence of these agricultural areas is probably very significant and this is called an agriculturally enriched loch. On the other hand, unlike Loch Lindores, Loch Kilconquhar is a bird sanctuary. Though it lies in an agricultural catchment, it was postulated that the effect of the dense bird population would predominate, especially during winter when there is a large population of migratory wintering ducks. In this context, therefore, this loch is referred to as a bird-enriched loch.

1.1) Loch Lindores

Loch Lindores lies 2 miles south of the Firth of Tay at Newburgh and about 20 miles from St. Andrews. The loch

is approximately a mile in length from south-east to north-west and about half a mile in breadth (Figure 1:1) and (Table 1:1).

It is situated at a latitude of 56° 20' N and longitude of 3° 50' W. With a surface area of 110 acres and a maximum depth of approximately three meters, it is relatively shallow.

Apart from arable farm land, livestock are also reared in the adjoining catchment area.

A wooden jetty which harbours several fishing boats, juts out from the south shore of the loch. This loch is also commercialized for fishing. Accordingly rainbow trout (Salmo gairdneri) are being bred for this purpose.

1.2) Loch Kilconquhar

Loch Kilconquhar is about two miles north of Elie, a small town on the coast of Fife. It is a very shallow circular lake about a mile in diameter. The village of Kilconquhar is situated on the north shore of the loch. Ultimately apart from this shore the loch is surrounded by marshes and beds of the common reed (Phragmites communis L.)

The loch has a maximum depth of approximately two meters and a surface area of 95 acres. A boat house which is situated on the south shore of the loch was used as a sampling station. An agricultural area is situated on the east side of the loch and there is a small stream flowing through this area to the east shore of the loch (Figure 1:2). The stream is the only inflow to the loch and it is occasionally blocked at the entrance by a dense growth of Phragmites, particularly in summer. The outflow is on the south shore and a spill

FIGURE 1:1 (Map 1)

(opposite)

Map of Loch Lindores, with sampling sites Station A (STN A) and Station B (STN B)

(Ordnance Survey Sheet No. 21 NE 1974)

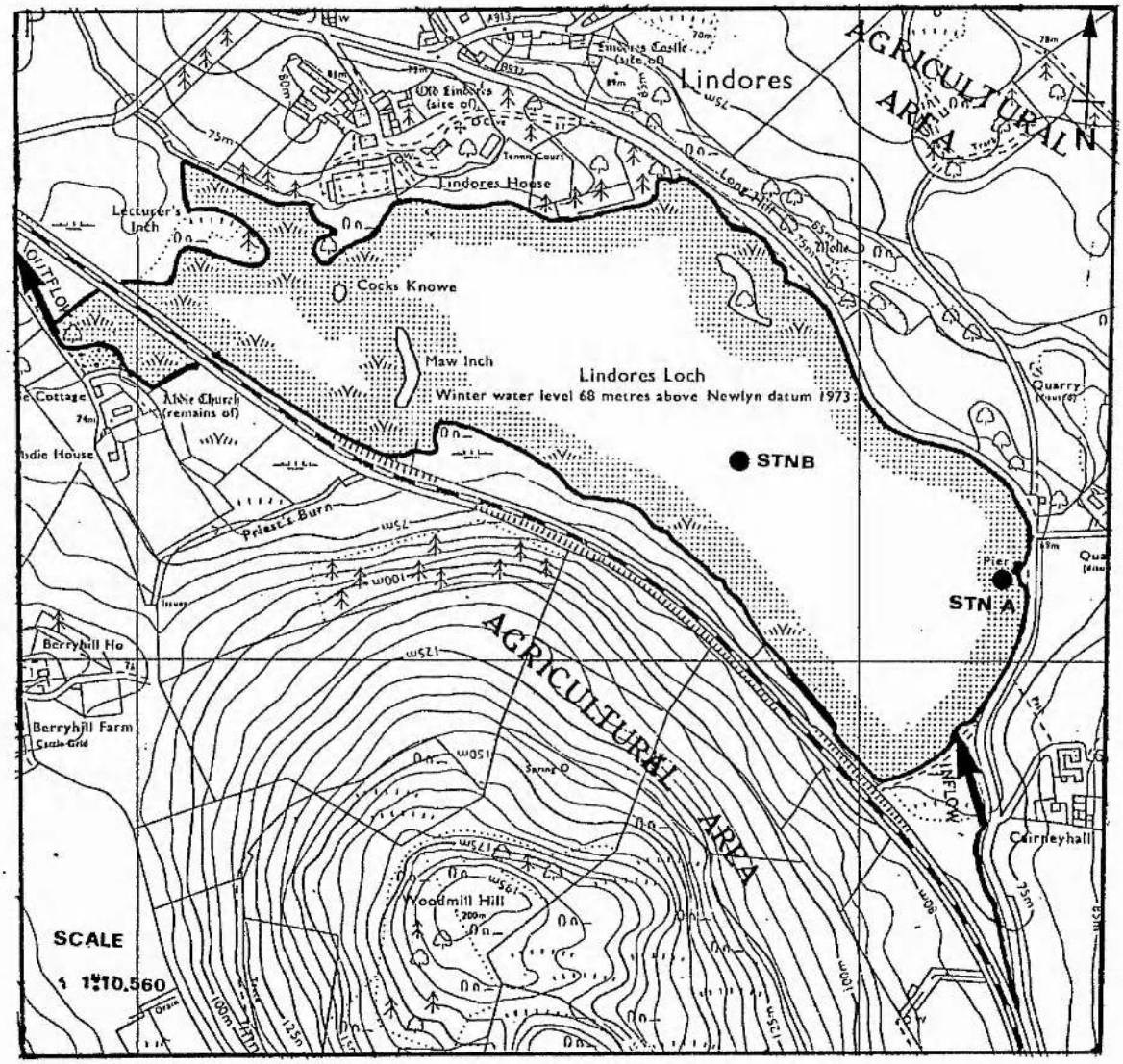

Lindores
AGRICULTURAL AREA
Lindores House
Lecturer's Inch
Cocks Knowe
Maw Inch
Lindores Loch
Winter water level 68 metres above Newlyn datum 1973
STNB
STN A
Priest's Burn
Abbie Church (remains of)
Berryhill Ho
Berryhill Farm
AGRICULTURAL AREA
Woodmill Hill
Curneyhall
INFLOW
SCALE
1 1:10,560

Table 1:1

Some limnological data for Loch Lindores and Loch Kilconquhar derived mainly from Bathymetrical Survey (1910) and Spence (1964).

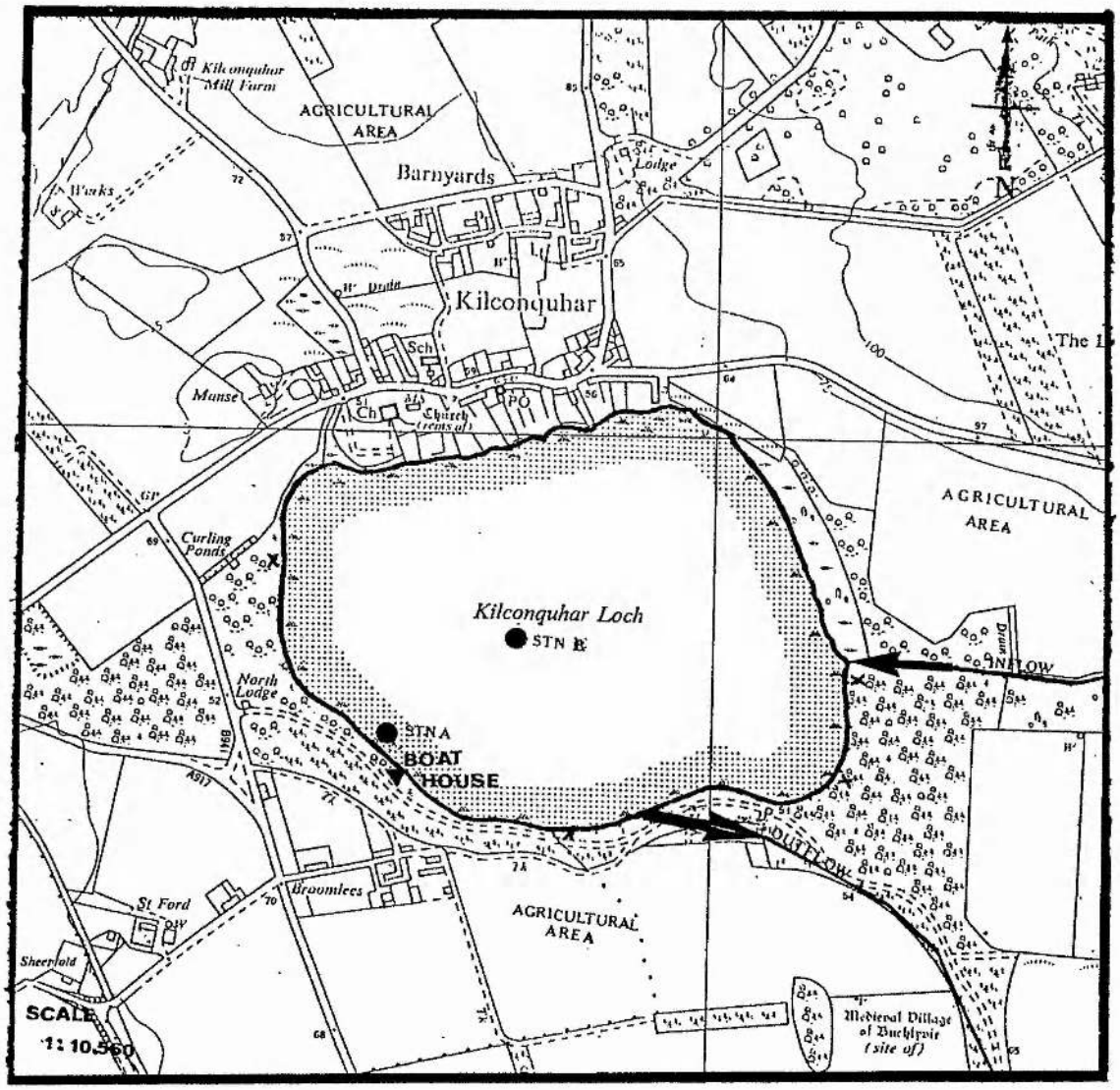
	Loch Lindores	Loch Kilconquhar
Origin	Kettle-hole in fluvio-glacial deposits	Kettle-hole in 30.5 m raised beach
Elevation	222 ft. (67.67 meter)	49 ft. (14.94 meter)
Surface area	110 acres (445,156 sq. meter)	95 acres (384,453 sq. meter)
Volume	24×10^6 cu. ft. (679,608 cu. meter)	16×10^6 cu. ft. (483,072 cu. meter)
Maximum depth	10 ft. (3.05 m)	6 ft. (1.83 m)
Mean depth	5 ft (1.52 m)	4 ft. (1.22 m)

FIGURE 1:2 (Map 2)

(opposite)

Map of Loch Kilconquhar, with sampling sites Station A (STN A) and Station B (STN B). (X) points along the shore where birds were observed. Scale 1:10.560 or 6 inches to 1 mile.

(Ordnance Survey Sheet No. 44 EE)


Kilconquhar Mill Farm
AGRICULTURAL AREA
Barnyards
Lodge
Works
Kilconquhar
Manse
Sch
Ch
Church (remains of)
PO
Curling Ponds
Kilconquhar Loch
STN B
STN A
BOAT HOUSE
North Lodge
INFLOW
OUTFLOW
AGRICULTURAL AREA
AGRICULTURAL AREA
St Ford
Broomlees
Sheepfold
Medieval Village of Buchlyvie (site of)
SCALE
1: 10,560

way which is situated about 50 metres down-stream from the outflow is used to control the water level of the loch.

The marshes and Phragmites reed beds provide an excellent breeding ground for many species of waterfowl. Unlike Loch Lindores, it is not used for fishing; instead it is used for bird shooting, particularly in winter. So far, the landowner is still trying unsuccessfully to rear fish commercially, presumably failing because of the highly eutrophicated state of the loch.

Field sampling

The routine shore sampling for both lochs was done almost every fortnight, from February 1979 to March 1981, in Loch Lindores on the south shore where there is a wooden jetty and in Loch Kilconquhar on the south-east shore near the boat house. These places are referred to as Station A.

In order to study any nutrient and phytoplankton stratification of the loch water column, the deepest part of the studied lochs were chosen and these places are referred to as Station B. Since the lochs are relatively shallow, water samples were collected from the respective lochs at 0.5 m depth intervals.

Station B in Loch Lindores is located in the south basin and about a quarter mile from the jetty. Fortunately permission was granted by the loch's owner to use a fishing boat for sampling purposes.

Station B in Loch Kilconquhar is also approximately at the centre of the loch. A departmental rubber dinghy was used to take the water sample from this place. It was

normally launched from the south-east shore near the boat house and the distance was about a half mile.

Water samples from Station A were easily collected by dipping polythene bottles. Water sampling from Station B was, however, more difficult. In this case, a three meter polythene hose with a diameter of three inches was used (Figure 1:3). A 10 kilogram weight was fastened at one end of the tube to ensure that it would stretch to the required depths, precisely at an interval of 0.5 m in the water. A rope was also tied at the same place so that this end could be conveniently pulled out of the water. At the other end, a rubber stopper was used to plug the hose, so that the water samples would stay inside. After sampling, the stopper was removed and the water was poured into the prepared labelled bottles which would be further analysed in the laboratory.

Loch sediment

A special sediment grab of area 15.5 x 15.5 cm^2 was used to take samples from the top part of the loch sediments at Station B of the respective lochs. The sediment samples were later analysed for total phosphate, kjeldahl nitrogen and sedimentary chlorophyll in the laboratory.

Dissolved oxygen (DO) concentration

Each water sample was carefully collected in a 250 ml stoppered bottle, care being taken not to trap any air bubbles.

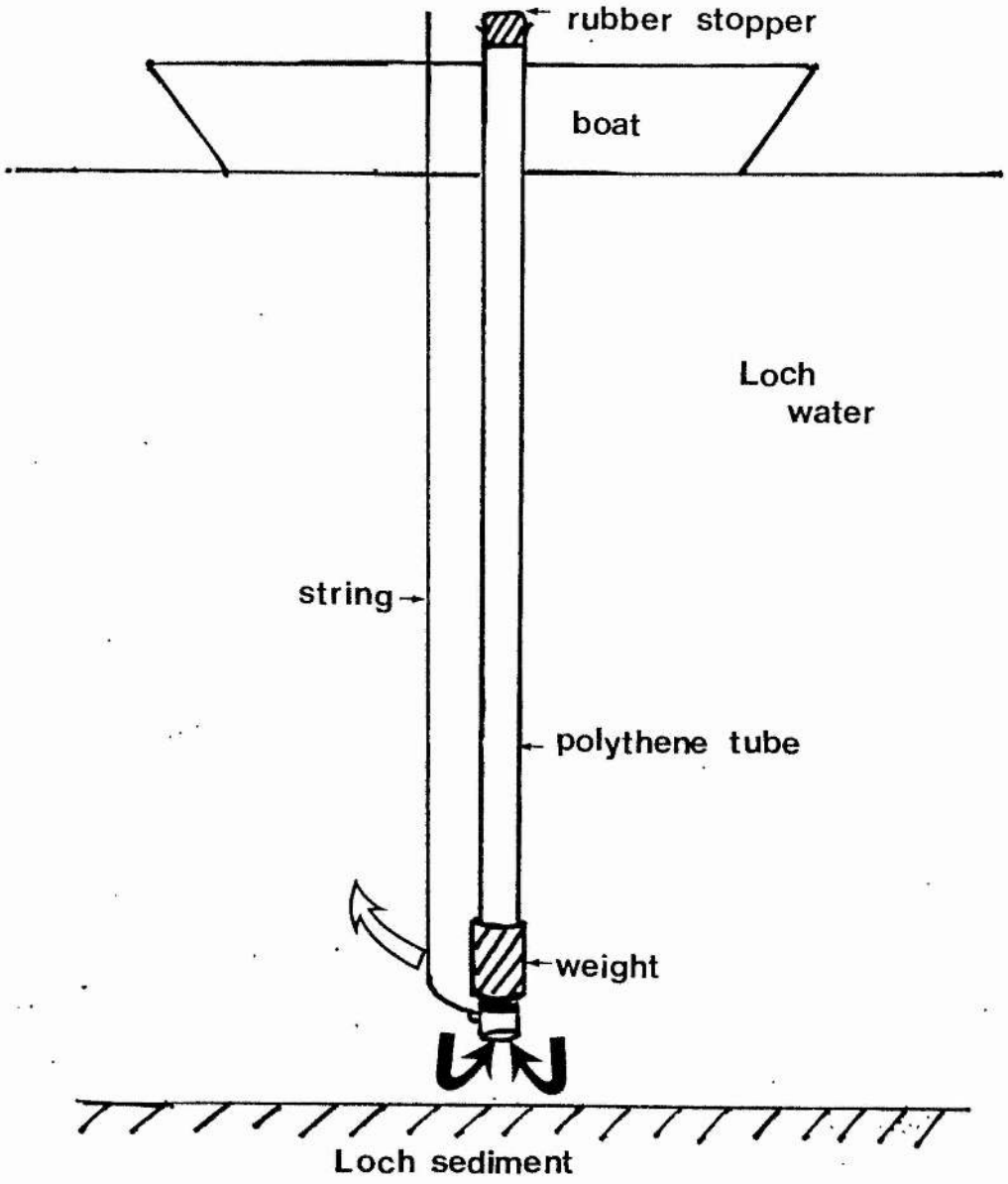
The oxygen-bottle stopper was removed within a few minutes of filling and a) 1.25 ml manganous sulphate and b) 1.25 ml Winkler's reagent were added to it. The stopper

FIGURE 1:3

(opposite)

Samples from Station B were taken by using 3 m polythene tube.

Fig. 1:3


rubber stopper
boat
Loch
water
string
polythene tube
weight
Loch sediment

was firmly replaced and the mixture was thoroughly shaken. A precipitate of manganous hydroxide was formed. This initial stage of the analysis was done in the field.

In the laboratory 2.5 ml sulphuric acid were introduced to the bottle and the mixture was well shaken to ensure the precipitate had fully dissolved. Then the manganic ions in acid solution oxidized iodide to tri-iodide (I_3^-) and free iodine. A rough estimate of the amount of oxygen present in the sample can be made by noting the depth of colour of the iodine at this stage.

The sample was then transferred to a 100 ml conical flask and titrated with 0.0125 N thiosulphate until only a faint yellow colour remained. Then five drops of starch indicator were added to take the titration to the end-point. This method is based on Mackereth et al. (1978).

The reagent used was a modification of Winkler's original reagents.

a) Manganous sulphate solution,

240 g $MnSO_4 . 4H_2O$ was dissolved in water and then diluted to 500 ml.

b) Winkler's reagent,

200 g sodium hydroxide was dissolved in 280 ml distilled water. Then 450 g sodium iodide was added and diluted to 500 ml.

c) 0.1 N sodium thiosulphate,

24.82 g $Na_2S_2O_3 . 5H_2O$ was dissolved in distilled water and made up to 1 litre.

d) Starch solution,

A slurry of potato starch was added to 100 ml boiling

distilled water (1 g shaken in about 10 ml of water in a test tube). It was then filtered and stored in a refrigerator.

e) Sulphuric acid,

50% v/v solution.

Occasionally a portable oxygen meter, Beckman Field Lab. analyzer was used. Calibrated against a Winkler analysis.

pH

pH of the water sample was taken by dipping a combined electrode connected to a pH meter Pye model 290. Before the reading was taken, the electrode was first dipped into a suitable buffer solution.

Conductivity

Conductivity of water samples was measured with a conductivity meter model MC mark V.

Temperature

Air and water temperatures were taken with an ordinary thermometer (E-MIL PERMA-LINE PAT. No. 1120773).

Alkalinity

In most natural water, bicarbonates and sometimes carbonates are present. These salts are hydrolyzed in solution because of the weakness of carbonic acid ($H_2 CO_3$), with the production of hydroxyl ions and consequent rise in pH:

$$M^+ + HCO_3^- + H_2O \rightleftharpoons M^+ + H_2 CO_3 + OH^-$$

The concentration of bicarbonate in solution can therefore be determined by titrating the sample with standard acid until the above equilibrium has moved completely to the right, with all the carbonic acid then present as undissociated H_2CO_3 or dissolved as CO_2. Since this occurs when the pH has been reduced to approximately 4.5, an indicator is chosen to give a colour change at this pH.

The reagents used were:

a) 0.01 N hydrochloric acid,

This was made by dilution of concentrated hydrochloric acid.

b) Indicator,

BDH 4.5 indicator.

100 ml of water sample was placed in a 250 ml conical flask and then was added with five drops of indicator. It was then titrated with 0.01 N HCl until the colour of the sample assumed a pale pink flusk. This method is based on Mackereth (1978).

Light

Light readings were taken by using a Lamda meter L_1-185, recording PAR (photosynthetically available radiation) over 400-700 nm. The sensor was lowered to various depths, at 0.25 m intervals in Loch Kilconquhar and 0.50 m intervals in Loch Lindores. The light entering the surface is expressed in the following relationships based upon Lambert's law.

$$I_d = I_o\, e^{-kd}\ (PAR)$$

in which I_o is the original intensity of the entering light, I_d the measurement of intensity incident at depth d, and e is

the base of natural logarithms. $K_{d(PAR)}$ is a constant, describing the rate at which light of defined wavelengths, here PAR, becomes attenuated or extinguished, with increasing water depth. $K_d(PAR)$ is the vertical diffuse attenuation coefficient for downwilling irradiance (400-700 nm).

Laboratory

a) Water chemistry

All glassware was cleaned before use by standing in hot chromic-sulphuric acid mixture for several minutes followed by thorough washing with distilled water before each determination.

A special millipore was used to filter 100 ml of water sample through 0.45 um membrane filter. The filtrate would subsequently be used for dissolved silica (SiO_2-Si), soluble nitrate-nitrogen (NO_3-N) and soluble reactive phosphate (SRP; orthophosphate PO_4-P) analysis. The residue membrane filter would be used for phytoplanktonic chlorophyll analysis.

Dissolved silica

Dissolved silica (Soluble reactive silicate; SiO_2-Si) was analysed after acidification with oxalic acid and then reaction with molybdate which eventually reduced silica to intensely coloured silicomolybdenum blue. The resulting absorbance was measured spectrophotometrically at 810 nm. A calibration graph was prepared in order to determine the SiO_2-Si concentration of the water. The reagents used were as follow:

a) Acid ammonium molybdate:

2 g ammonium molybdate was dissolved in 70 ml distilled

water. It was then added to 6 ml hydrochloric acid and diluted to 100 ml.

b) Oxalic acid, $(CO\ OH)_2.2H_2O$:

10% w/v solution.

c) Methol-sulphite solution:

6 g sodium sulphite ($Na_2SO_3.7H_2O$) was dissolved in water. Later 5g metol was added. Subsequently the volume is made up to 250 ml.

d) Reducing agent:

30 ml sulphuric acid was added to 100 ml of water. To this mixture were further added 100 ml metol-sulphite solution (c) and 60 ml oxalic acid solution (b), the whole being finally diluted to 300 ml.

e) Silicon standard:

0.6714 g dry sodium fluorosilicate ($Na_2\ SiF_6$) was dissolved in 1 l distilled water.

This method is modified by Mackereth's (1978) modification of Mullin and Riley (1955).

Nitrate-nitrogen

Since the filtered water sample was considered clear, soluble nitrate-nitrogen (NO_3-N) was directly determined at the absorbance of 220 nm UV (Ultra violet) light by a Beckman DB-GD Spectrophotometer. A calibration graph was prepared to determine the concentration of the water sample. This method was based on that of the American Public Health Association (1971).

This particular method is relatively simple because it can be applied directly to the analysis of water without recourse

to evaporation or precipitation. No sample preparation is required, unless suspended material is present, in which case the impurities can be removed by centrifugation, filtration and dilution.

Soluble reactive phosphate

Soluble reactive phosphate (orthophosphate; PO_4-P) in this context is referred as soluble phosphate. The method used is principally based on the reaction of orthophosphate in acid solution with ammonium molybdate to form phosphomolybdic acid and subsequently reduced by stannous chloride to the molybdenum blue complex.

The reagents used were:

a) 4N H_2SO_4:

112 ml concentrated sulphuric acid was diluted to 1 l.

b) 0.96% molybdate:

9.6 g $(NH_4)_6\ Mo_7\ O_{24}.4H_2O$ was dissolved in 1 l distilled water.

c) 10% ascorbic acid:

10 g ascorbic acid were dissolved in 80 ml distilled water.

d) Antimony tartrate:

0.667 g potassium antimony tartrate ($KSbO.C_4H_4O_6$) was dissolved in 250 ml distilled water.

e) Mixed reagent:

Equal volumes of ascorbic acid solution and antimony tartrate solution were mixed. Only enough solution was prepared for immediate use.

10 ml water sample was placed in 25 ml volumetric flask.

2.5 ml each of sulphuric acid and molybdate solution were added. The mixture was diluted to 20 ml with distilled water. Finally 2 ml mixed reagent was added and the mixture was diluted to 25 ml. Samples were then measured at an absorbance of 890 nm in a Beckman DB-GD spectrophotometer. A calibration graph was prepared for determining the unknown concentration of the water sample. This method was based on Harwood et al. (1969).

Kjeldahl Nitrogen and Total Phosphate

As stated before, for kjeldahl nitrogen and total phosphate, the unfiltered water sample was used. Initially the sample was digested with sulphuric acid (H_2SO_4 (1+1)) with the help of catalyst, in a kjeldahl flask and then neutralized with sodium hydroxide.

The total nitrogen in the loch water is referred to as kjeldahl nitrogen in this text, partly because the most critical step in the kjeldahl procedure is the sulphuric acid oxidation of organic compounds. According to Skoog and West (1970), during the operation the fate of nitrogen is highly dependent upon the form in which it occurs in the original compounds and it is preferably analysed according to the oxidized state of the sample as nitrate-nitrogen.

The polyphosphate (mainly total phosphate) was hydrolysed to orthophosphate before it was determined.

Subsequently the sample was analysed for kjeldahl nitrogen using the same method as described for NO_3-N and for the total phosphate; the same method as described by Harwood et al. (1969) was used.

Sedimentary chemistry

1 gm fresh weight of loch sediment was dried in the oven for 24 h to obtain a constant dry weight.

Another 1 g fresh loch sediment was transferred to a 30 ml kjeldahl flask and subsequently heated on a mantle with 5 ml nitrogen-free sulphuric acid and a kjeldahl tablet (as a catalyst). To fully oxidize the sample, 0.5 ml of 50% hydrogen peroxide was carefully added to the flask. The heating was done in the fume cupboard. This method is mainly based on Slater and Boag (1978) and Guppy and Wood (1978).

The digested semiment was centrifuged and the solution was then neutralized with sodium hydroxide and diluted to 50 ml. This solution was used for total phosphate and kjeldahl nitrogen determinations.

Total phosphate was determined on 2 ml solution, after dilution 1:25. The analysis followed Harwood (1969) as previously described for soluble phosphate.

Two ml of the solution were diluted to 50 ml, and this solution was used for determination of kjeldahl nitrogen, following the same method for NO_3-N (American Public Health Association, 1971) as already described.

Productivity

Phytoplankton

The filter paper which was covered with planktonic chlorophyll was initially dried in the freezer overnight and later extracted in 5 ml 90% acetone and stored in the dark for a further 24 h. Readings were taken at wavelengths of 664 nm for chlorophyll a, 647 nm for chlorophyll b and 630 nm for

chlorophyll c. Calculations for the respective chlorophylls were based on Jeffrey and Humphrey (1975).

$$\text{Chlorophyll } \underline{a} = 11.85\ E_{664} - 1.54E_{647} - 0.08E_{630}.$$

$$\text{Chlorophyll } \underline{b} = 21.03\ E_{647} - 5.43E_{664} - 2.66E_{630}.$$

$$\text{Chlorophyll } \underline{c} = 24.52\ E_{630} - 1.67E_{664} - 7.60E_{647}.$$

Then, mg chlorophyll ($\underline{a}$, $\underline{b}$, or c)/m^3

$$= \text{Chlorophyll } (\underline{a}, \underline{b}, \text{ or } \underline{c}) \times \frac{v}{V} \times \frac{10^3}{p}$$

V = volume of sample filtered in ml

v = volume of extract in ml.

p = is the path length of cuvette in cm.

Lugol's solution was used to sediment the 250 ml loch water needed for phytoplankton studies. A Watson Barnet Bactil 60 microscope was used to identify and count the phytoplankton. West and Fritsch (1968), Belcher and Swale (1978) and Prescott (1970) were used as references to identify the algae.

Submerged macrophytes (Loch Kilconquhar)

Generally the submerged macrophytes were harvested from rooting depths of 0.25 m, 0.50 m and 0.75 m from the south-east shore near the boat house. A perspex corer with an area of 55.4 sq cm was used to take the plant samples, in replicates of five. Plant samples were placed in plastic bags for further study in the laboratory. Approximately half of the fresh plants in the area of 27.7 sq cm was extracted with 90% acetone, added with magnesium carbonate.

The plant material was later ground and homogenised to ensure complete extraction. Absorbance was read with a spectrophotometer at 665 nm for chlorophyll a and 645 nm for

chlorophyll b. The other half was incubated at 100°C for 24 h to obtain oven dry plant weight. Calculation was based on Westlake (1974)

ug chl a per sample

$= (11.6\ D_{665} - 1.3 D_{645})\ V/l$

ug chl b per sample

$= (19.1\ D_{645} - 4.7\ D_{665})\ V/l$

V = Vol. of acetone extract in ml.

l = length of spectrophotometer cell in cm.

Sedimentary chlorophyll

A top layer of the loch sediment was analysed for sedimentary chlorophyll. About 2 g fresh sediment were homogenised on a glass plate with a spatula. Half the sample was dried at 100°C for 24 h in the oven. The other half of the sample was extracted in 25 ml of solvent (90% acetone + 0.5 dimetyl aniline) and allowed to stand overnight in the freezer. It was then filtered through Whatman No. 80 filter paper. The residue was repeatedly extracted until all the colour had been removed. Colour density was determined in a spectrophotometer at wavelength of 667 nm. Calculation was based on J.R. Vallentyne (1955).

Sedimentary chlorophyll

$$= \frac{\text{Density reading x filtered volume}}{\text{dry weight of mud extracted}}$$

I. 2) RESULTS

2.1) Nutrients

The overall dissolved silica (SiO_2-Si) concentration for Loch Lindores was moderately high and reached a maximum value of 4.00 mg/l in Dec. 1979. However, the SiO_2-Si concentration was extremely low in early Spring 1979, during the dense growth of Asterionella formosa (Figure 1:4a).

Initially, in the year 1979, the SiO_2-Si concentration for Loch Kilconquhar was low. Nevertheless, it gradually increased in Summer 1980 but dropped again in Winter of the same year. This fall was probably largely due to the diatom bloom of Stephanodiscus sp when the concentration decreased to a minimum of 0.01 mg/l.

As both lochs are relatively shallow, no significant SiO_2-Si stratification occurred, except for a slight increase in SiO_2-Si concentration at 1.5 meter in Loch Kilconquhar in September 1979 (Figure 1:5a). This was probably due to sediment release which will be discussed further in the next chapter.

The soluble Nitrate-Nitrogen NO_3-N were high in both the lochs studied (Figure 1:4b). In Lindores, NO_3-N was extremely high in late Winter where it reached a maximum of 3.3 mg/l in February 1980. The concentrations were also consistently high in Loch Kilconquhar, reaching a maximum value of 2.3 mg/l during the blue-green bloom of Aphanizomenon flos-aquae in August 1980.

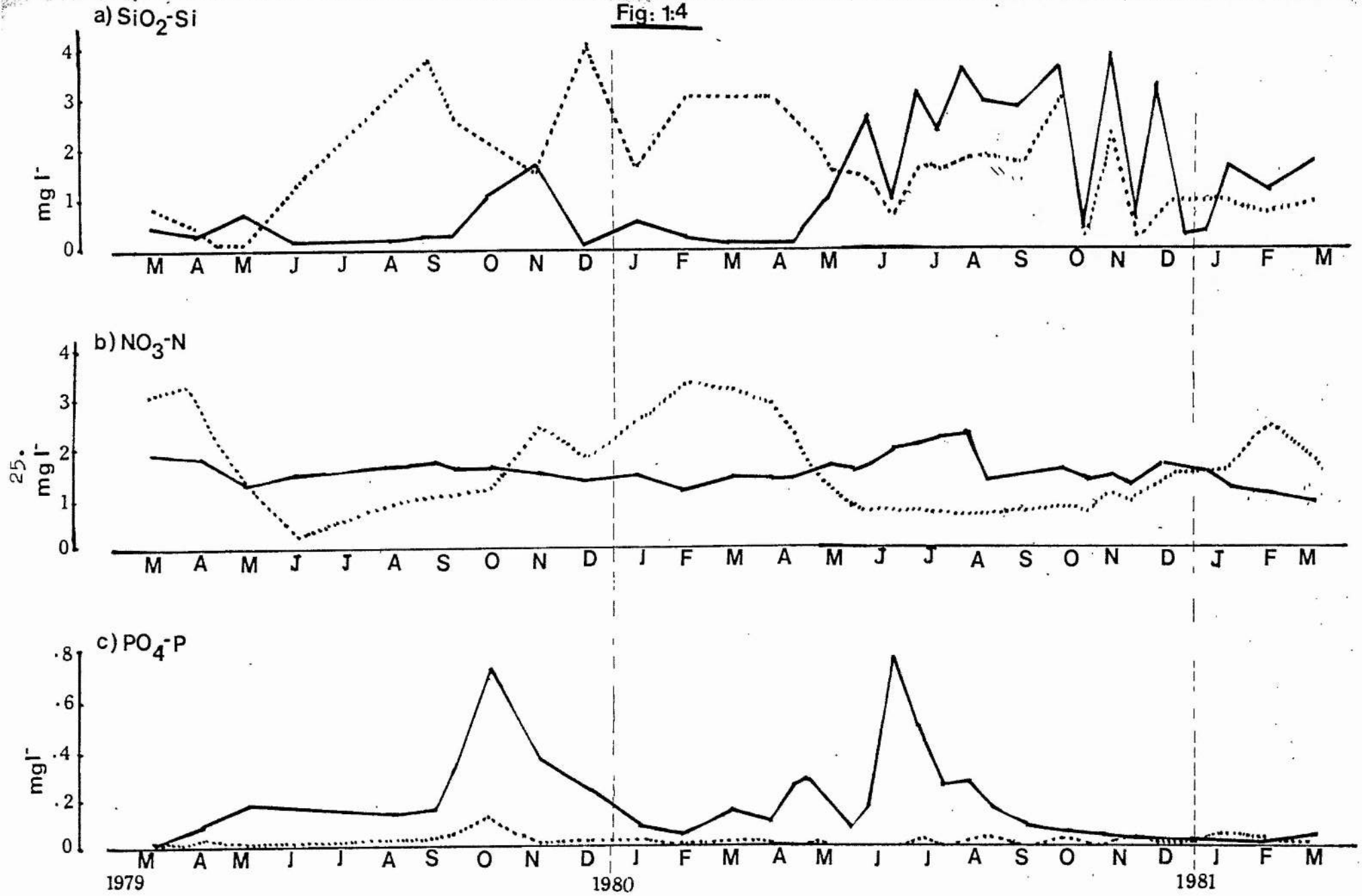
The total kjeldahl nitrogen concentrations were high in both lochs reaching maxima 8.8 mg/l in December 1980, and

FIGURE 1:4

(opposite)

The seasonal changes in a) SiO_2-Si, b) NO_3-N and c) PO_4-P concentrations at Station of Loch Lindores (-.-.-.-) and Loch Kilconquhar (———) from March 1979 until March 1981.

Fig: 1:4


a) SiO_2-Si
mg l⁻
4
3
2
1
0
M A M J J A S O N D J F M A M J J A S O N D J F M
b) NO_3-N
25.
mg l⁻
4
3
2
1
0
M A M J J A S O N D J F M A M J J A S O N D J F M
c) PO_4-P
mg l⁻
·8
·6
·4
·2
0
M A M J J A S O N D J F M A M J J A S O N D J F M
1979
1980
1981

10 mg/l in November 1980, in Loch Lindores and Loch Kilconquhar respectively (Figure 1:6a).

There was no significant NO_3-N stratification in either loch, excepting a slight increase at 1.5 m in Loch Kilconquhar in summer 1979 (Figure 1:5b). This may be due to sediment release.

The Soluble Reactive Phosphate (PO_4-P; SRP) concentrations in Loch Lindores were generally low, particularly in early summer 1980 where it was below the limit of detection by the sensitive method used. On the other hand, the PO_4-P concentrations in Loch Kilconquhar were exceptionally high reaching maximum values of 0.72 mg/l in October 1979 and 0.78 mg/l in July 1980 (Figure 1:4c).

The total phosphate concentration in Loch Kilconquhar was also high compared with Loch Lindores (Figure 1:6b).

There was no PO_4-P stratification in Loch Lindores. In Loch Kilconquhar, however, PO_4-P at a depth of 1.5 m was very low than at other recorded depths, particularly in Summer and Autumn 1979 (Figure 1:5c). Apart from nutrient release, there may be several reasons to account for the low PO_4-P at 1.5 m, such as the high consumption of soluble phosphate by benthic algae and also, presumably by the submerged macrophytes.

2.2) Sediment chemistry

Deposited allochthonous materials from wildfowl faeces (Loch Kilconquhar) and agricultural run off (Loch Lindores and Loch Kilconquhar) and also autochtonous materials such as dense decaying algae and macrophytes, could strongly affect

FIGURE 1:5

(opposite)

The nutrient stratification, at Station B of Loch Lindores (---------) and Loch Kilconquhar (←———→), in the year 1979.

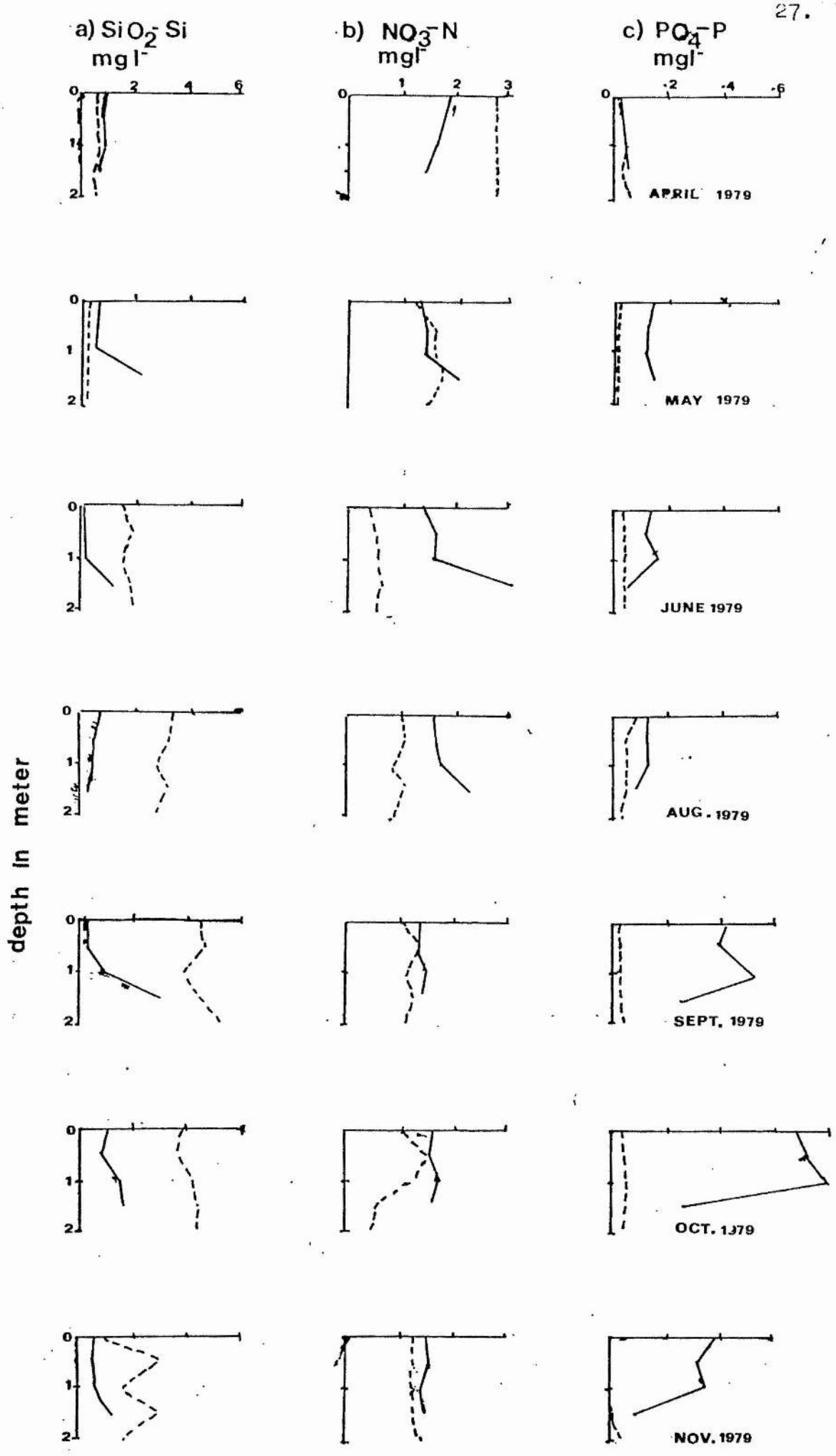

a) SiO_2-Si mg l^{-}
b) NO_3-N mgl^{-}
c) PO_4-P mgl^{-}
depth in meter
APRIL 1979
MAY 1979
JUNE 1979
AUG. 1979
SEPT. 1979
OCT. 1979
NOV. 1979

Fig. 1:5

FIGURE 1:6

(opposite)

The Kjeldahl Nitrogen and Total Phosphate concentrations at Station A for Loch Lindores (-------) and Loch Kilconquhar (——).

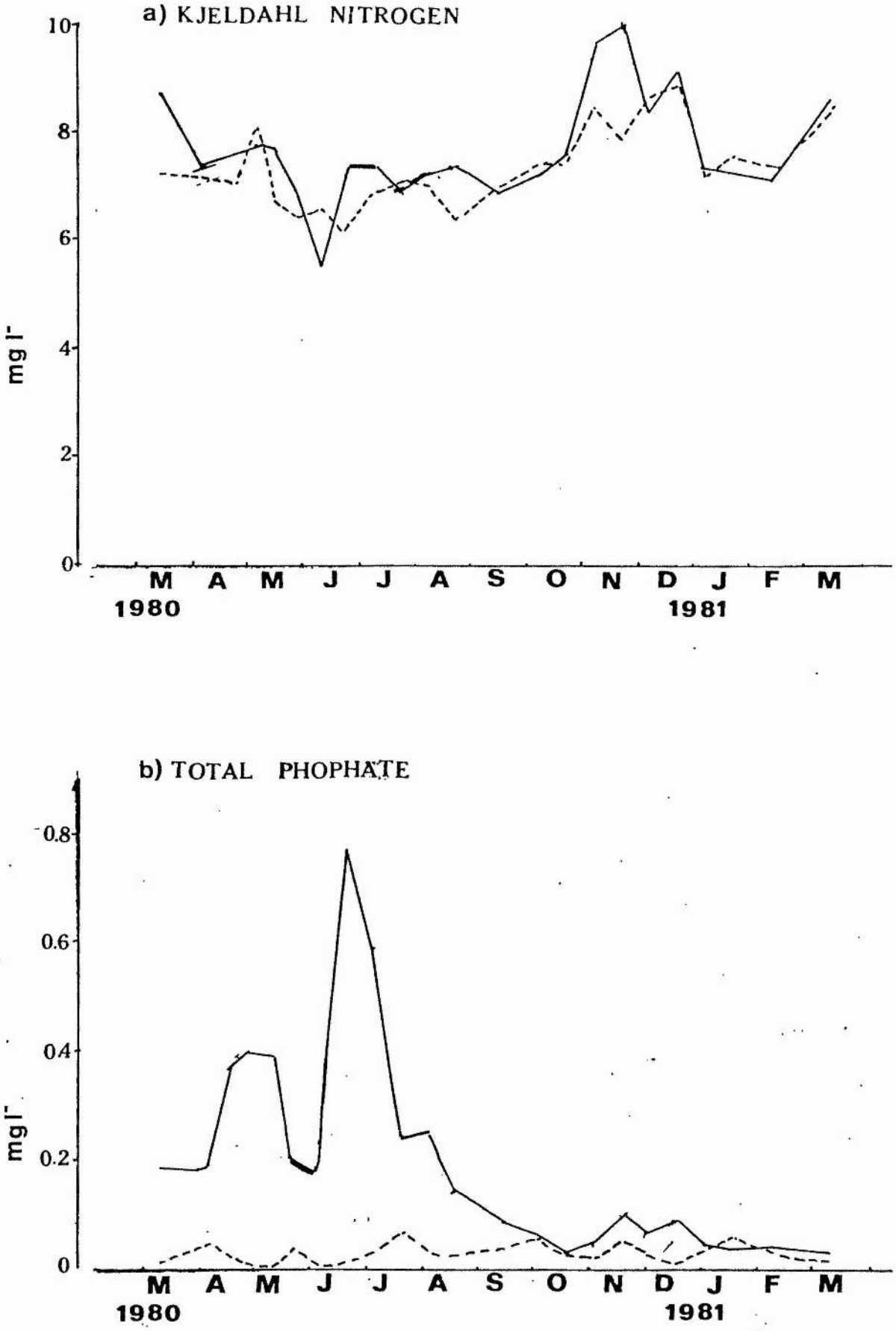

a) KJELDAHL NITROGEN
10
8
6
4
2
0
mg l⁻
M A M J J A S O N D J F M
1980
1981
b) TOTAL PHOPHATE
0.8
0.6
0.4
0.2
0
mg l⁻
M A M J J A S O N D J F M
1980
1981

Fig. 1:6

Table 1:2

Total phosphate and total kjeldahl nitrogen in mg/kg dry weight of sediments from Loch Lindores and Loch Kilconquhar. Results are mean of three samples ± 95% CL (n = 3).

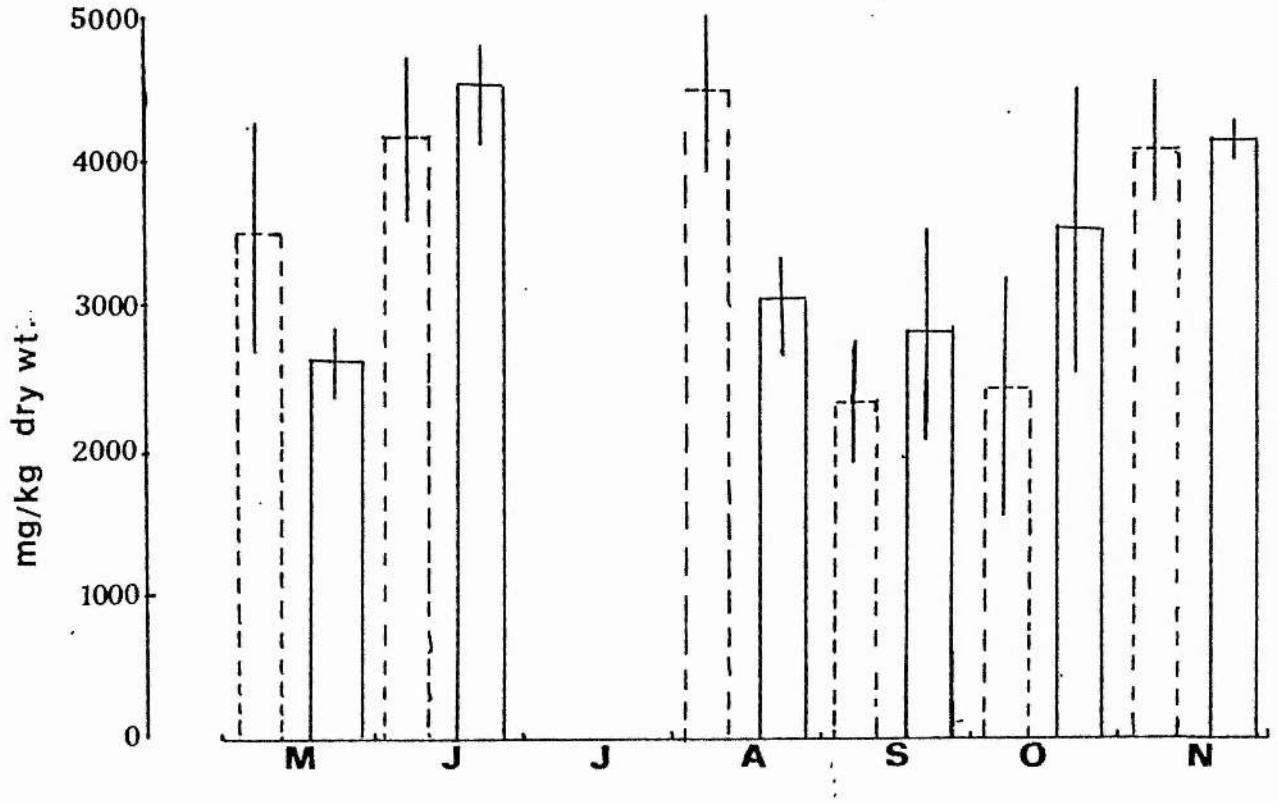
Date	Locality	Total Phosphate mg/kg dry wt.	Total Kjeldahl Nitrogen mg/kg dry wt.
11 May 1979	Lindores	1500 ± 467	3250 ± 920
	Kilconquhar	1580 ± 600	2600 ± 260
4 June 1979	Lindores	1820 ± 690	4225 ± 944
	Kilconquhar	1780 ± 645	4250 ± 668
22 Aug. 1979	Lindores	2440 ± 782	4226 ± 723
	Kilconquhar	840 ± 28	300 ± 563
10 Sept. 1979	Lindores	883 ± 322	2300 ± 793
	Kilconquhar	900 ± 70	2800 ± 377
17 Oct. 1979	Lindores	953 ± 93	2430 ± 1803
	Kilconquhar	1650 ± 620	3520 ± 2022
6 Nov. 1979	Lindores	1790 ± 779	4553 ± 117
	Kilconquhar	1936 ± 136	4566 ± 15
11 March 1980	Kilconquhar	1831 ± 646	3200 ± 113
29 May 1980	Kilconquhar	760 ± 45	2900 ± 680
9 July 1980	Kilconquhar	650 ± 79	3287 ± 360
22 Aug. 1980	Kilconquhar	1263 ± 39	3480 ± 740
13 Oct. 1980	Kilconquhar	1090 ± 329	3425 ± 368
3 Dec. 1980	Kilconquhar	2450 ± 151	5483 ± 1335

FIGURE 1:7

(opposite)

The Kjeldahl Nitrogen and Total Phosphate from Loch Lindores sediment (⁞⁞) and Loch Kilconquhar sediment (||) at Station B, in the year 1979.

a) KJELDAHL NITROGEN



b) TOTAL PHOSPHATE

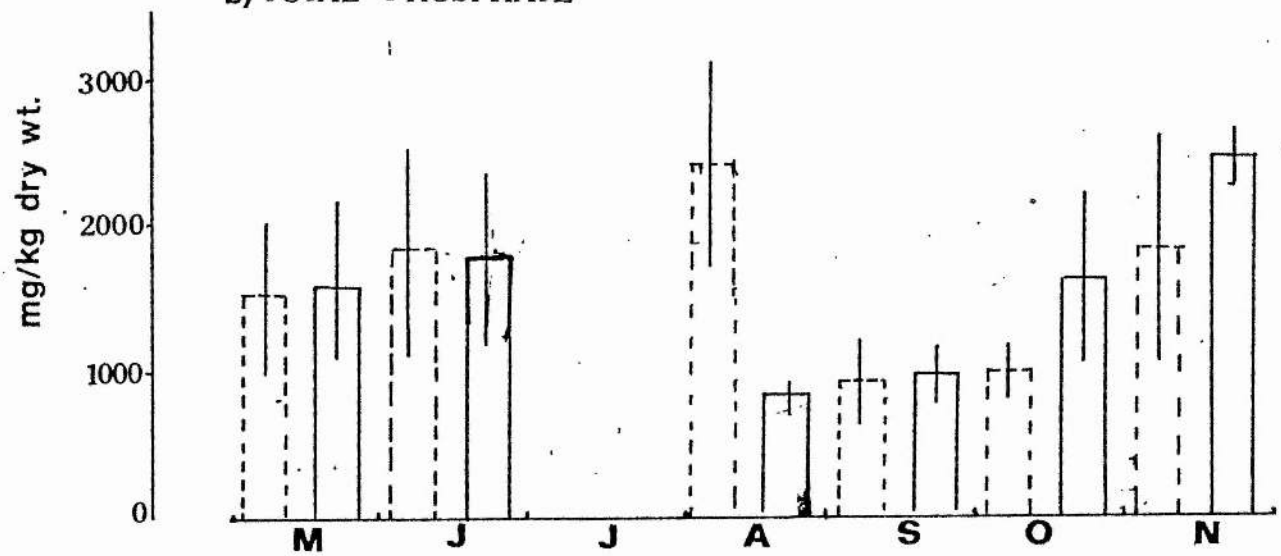


Fig. 1:7

the sediment in general and its chemistry in particular. In addition, sediment release may play a major role in bringing nutrients from the sediment to the overlying water.

Table 1:2 shows the variation in total kjeldahl nitrogen and total phosphate in sediments of both lochs. It seemed the values in Loch Kilconquhar were generally high in winter and rather lower in summer. Figure 1:7a;b also show the variations in total kjeldahl nitrogen and total phosphate in both lochs during the year 1979.

2.3) Dissolved oxygen (DO) concentration

Normally the increase in DO concentrations is inversely related to the rise in water temperatures. That is saturation quantity of DO concentration of loch water mainly depends on the water temperature but the presence of phytoplankton and water plants could contribute to an increase of DO in a loch, particularly during the day. Figure 1:8 clearly indicates that on ten sampling occasions in Loch Lindores, the DO values were above the saturation point compared with only six occasions in Loch Kilconquhar. Most of the time the readings in Loch Kilconquhar were far below saturation point. This is possibly due to the substantial amounts of oxygen consumed by bacterial activity in this loch, particularly at surface, of sediment during warm weather (Figure 1:9). Certainly as studied in Chapter 3, anaerobic conditions developed during this period.

No oxygen depletion was observed during summer in Loch Lindores and it, therefore, seems unlikely that aerobic conditions ever developed there.

FIGURE 1:8

(opposite)

Solubility of dissolved oxygen in relation to water temperature in Loch Lindores (O) and Loch Kilconquhar (●), at Station A, from March 1979 to March 1981. The straight line slope represents the saturation quantity of pure water.

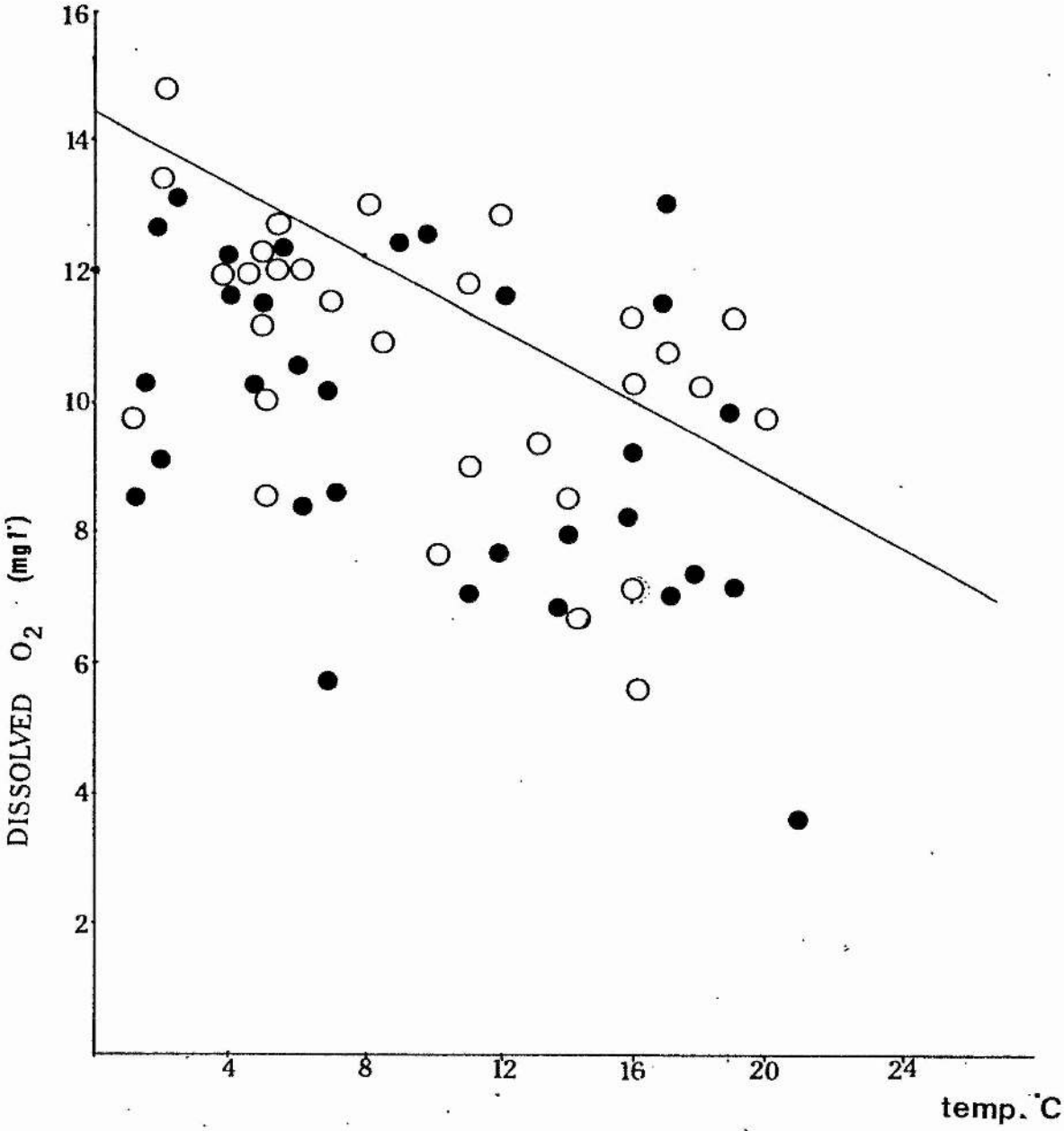


FIG. 1:8

FIGURE 1:9

(opposite)

Changes in Dissolved Oxygen (DO) concentrations at Station A in Loch Kilconquhar over a year period 1980-1981. Samplings (surface water samples) were done at 12 noon. Note the DO concentrations in summer were generally low.

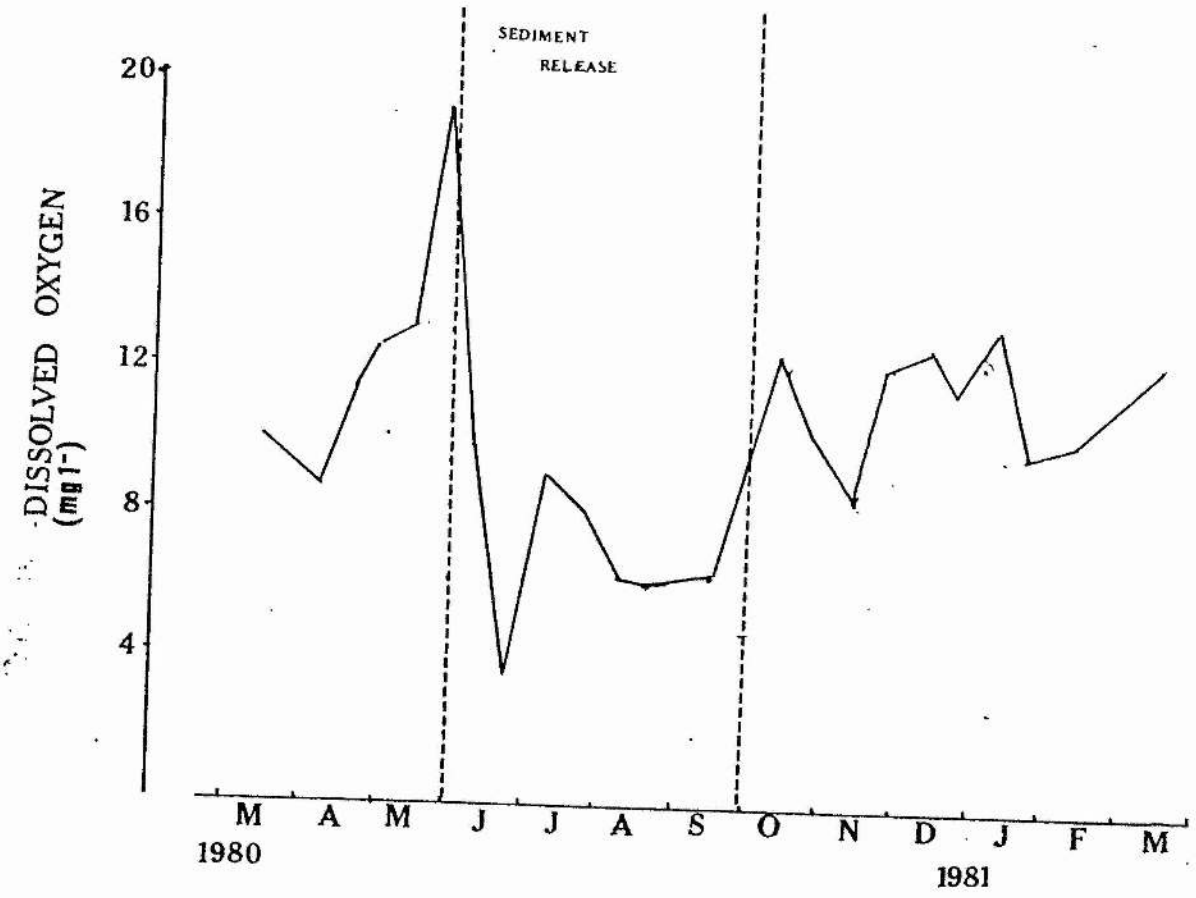

SEDIMENT
RELEASE
DISSOLVED OXYGEN
(mg l⁻¹)
20
16
12
8
4
M
A
M
J
J
A
S
O
N
D
J
F
M
1980
1981

FIG. 1:9

2.4) pH, conductivity and alkalinity

Loch Lindores and Loch Kilconquhar can be considered as alkaline lochs because the pH never falls below 7 (Figure 1:10a). The pH variation in Loch Lindores lay between 7.30 and 9.20. On the other hand, the pH variation in Loch Kilconquhar was between 7.60 and 10.40. The general trend for both lochs was a steady pH increase in summer, particularly during the algal blooms.

The conductivity of Loch Kilconquhar was higher than that of Loch Lindores (Figure 1:10b). Obviously Loch Kilconquhar has higher concentration of dissolved ions than Loch Lindores.

In Lindores, the alkalinity value dropped to a minimum of 0.75 meg l^{-} in January 1980; however, in early June 1980 it rose to a maximum value of 2 meg l^{-} (Figure 1:10c). The alkalinity level for Loch Lindores was always lower than that of Loch Kilconquhar. The alkalinity values for Loch Kilconquhar were generally high, particularly in summer 1980, reaching a maximum of 3.90 meg l^{-} in May 1980 and this coincided with pH maxima.

2.5) Light

Values for the diffuse attenuation coefficient k_{PAR} were 1.50 in Loch Lindores recorded on 28th September, 1979 and 4.40 in Loch Kilconquhar recorded on 29th May, 1980. At the time, it was observed that the phytoplankton densities were at their maximum values due to the blue-green algal blooms.

On the other hand where the k_{PAR} were low, at 0.60 for Loch Lindores, and 0.80 for Loch Kilconquhar, the phytoplankton densities were at their minimum values for each loch.

FIGURE 1:10

(opposite)

The seasonal changes in a) pH, b) conductivity and c) alkalinity at Station A of Loch Lindores (--------) and Loch Kilconquhar (————), from March 1979 to March 1981.

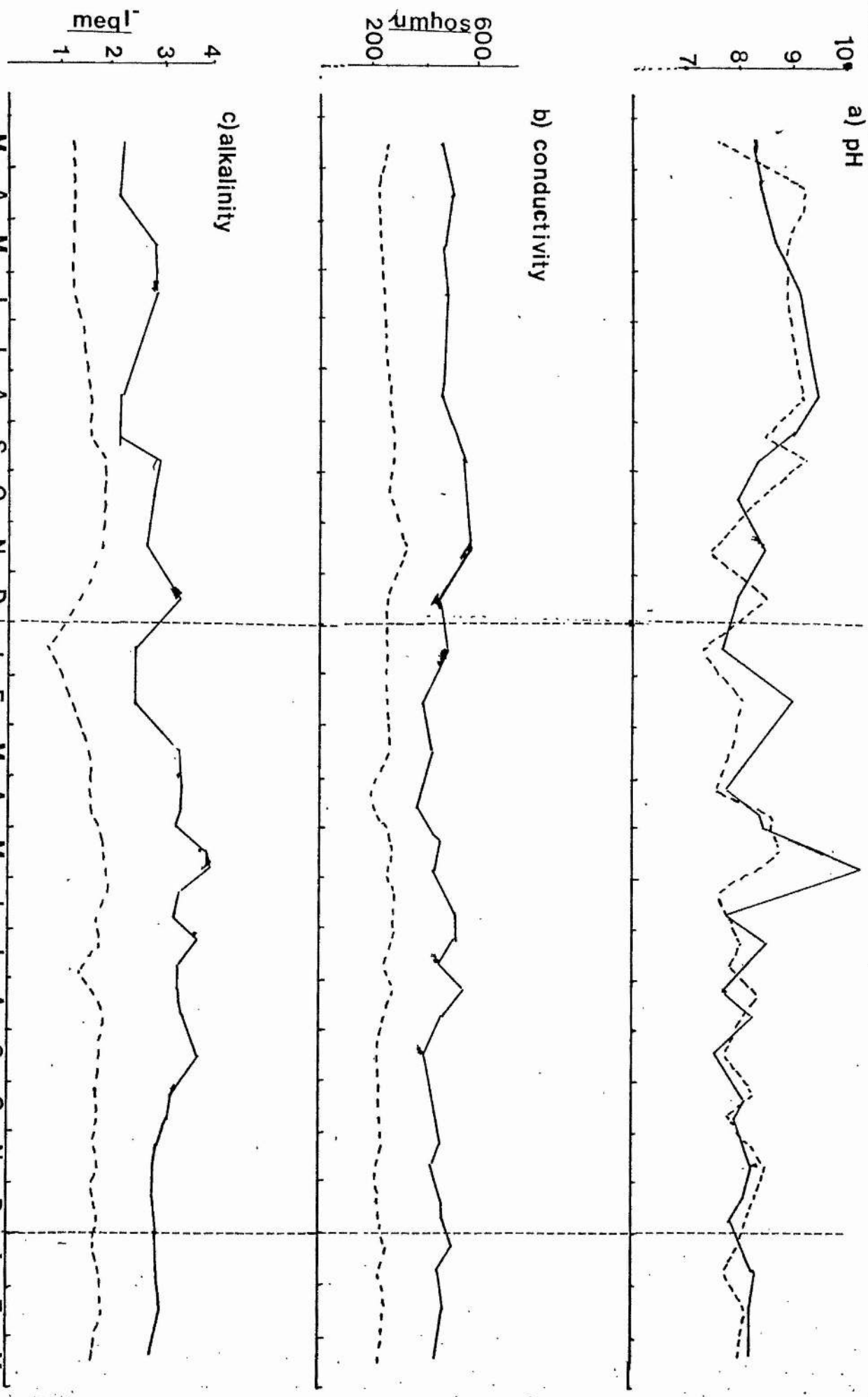

a) pH
10
9
8
7
b) conductivity
µmhos
600
200
c) alkalinity
meq l⁻
4
3
2
1
M A M J J A S O N D J F M A M J J A S O N D J F M
1980
1981

FIG. 1:10

Figures 1:11 and 1:12 show possible correlations between the k_{PAR} and chlorophyll a mg m^{-3} for both lochs. The slope in Loch Kilconquhar is ($y = 0.0263x + 0.325$) and steeper than the slope in Loch Lindores ($y = 0.00563x + 0.468$). This may be due to the high dissolved substances and non-algal particulate in Loch Kilconquhar.

2.6) Productivity

a) Phytoplankton

Figure 1:13 shows the seasonal variation in phytoplanktonic chlorophyll a concentration for Loch Lindores and Loch Kilconquhar. Chlorophyll a in Loch Lindores was initially high in 1979, particularly in September during the *Anabaena* bloom where it reached a maximum of 160 mg/m^3. However, it was extremely low for the subsequent year, except in February during a dense *Asterionella formosa* growth when it reached around 50 mg/m^3.

Overall phytoplankton productivity in Loch Kilconquhar was generally high with chlorophyll a never dropping below 10 mg/m^3, with a peak of 357.20 mg/m^3 during *Anabaena* bloom in May 1980. The high plankton densities during winter 1979-80 were attributed to Diatom species such as *Stephanodiscus sp.* It is interesting to note that there was a second appearance of blue-green algal bloom (*Aphanizomenon flos-aquae*) in late summer 1980.

There was a considerable variation between years in the seasonal succession of algal genera. The overall sequence during the study period from February 1979 to March 1981 in Loch Lindores and Loch Kilconquhar are shown in Table 1:3.

FIGURE 1:11

(opposite)

Possible correlation between k_{PAR} and chlorophyll a mg/m^3 at the depth of 1 m in Loch Lindores.

FIG. 1.11

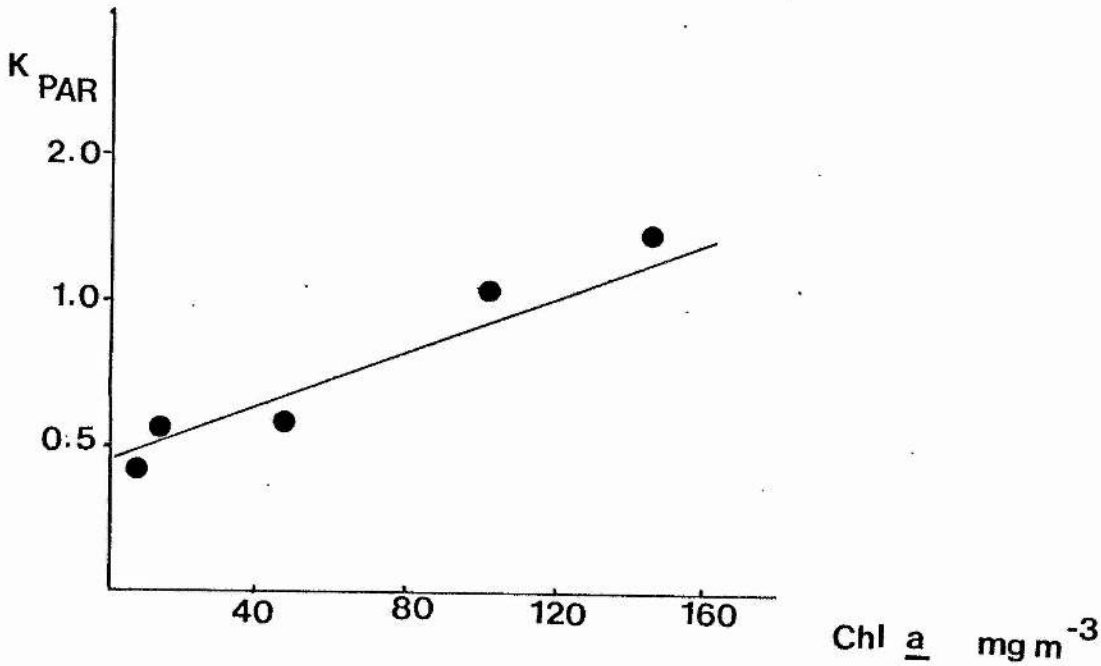


FIGURE 1:12

(opposite)

Possible correlation between k_{PAR} and chlorophyll a mg/m^3 at the depth of 1 m in Loch Kilconquhar.

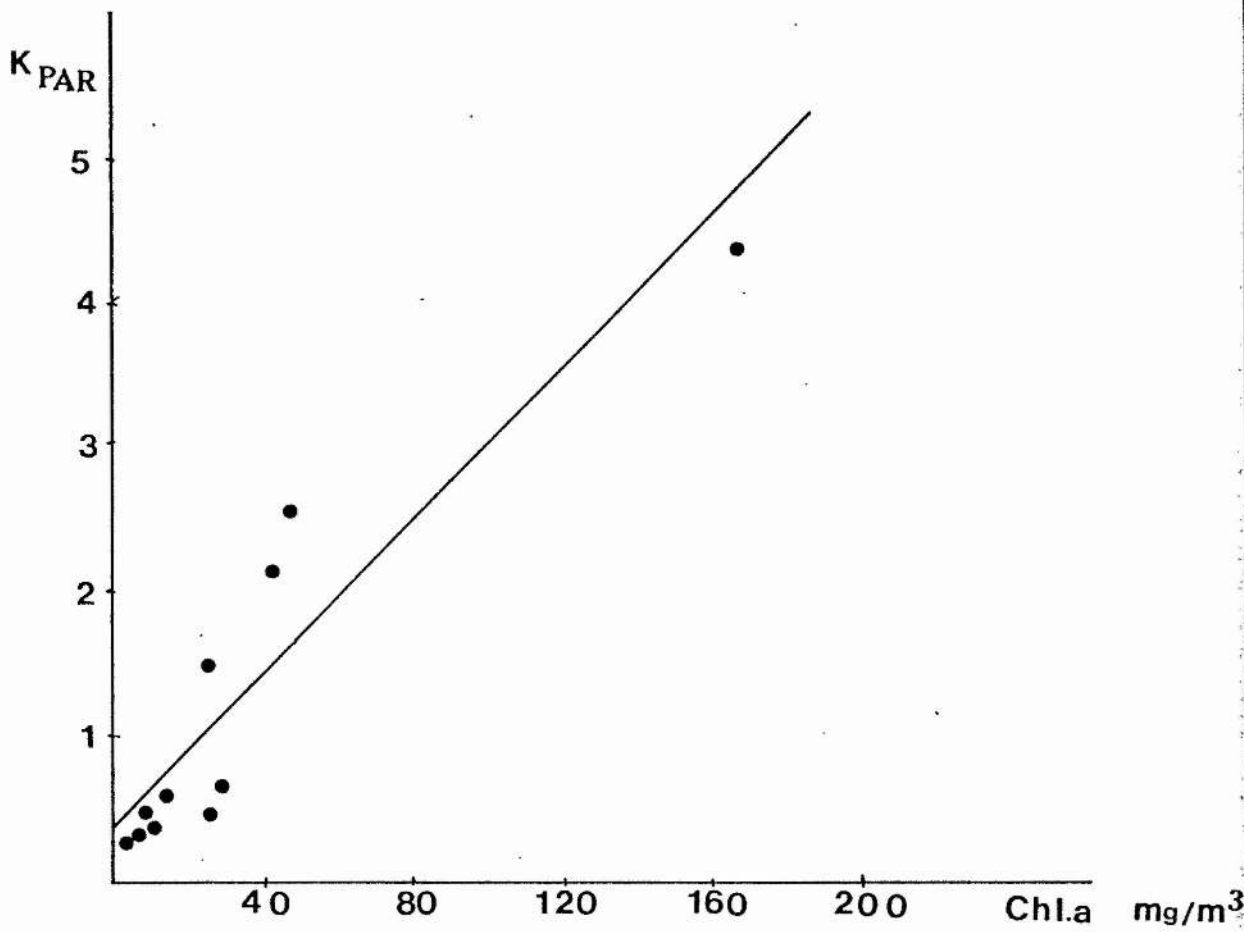


FIG. 1:12

FIGURE 1:13

(opposite)

The phytoplanktonic chlorophyll *a* at Station A for Loch Lindores (----------) and Loch Kilconquhar (———), from March 1979 to March 1981.

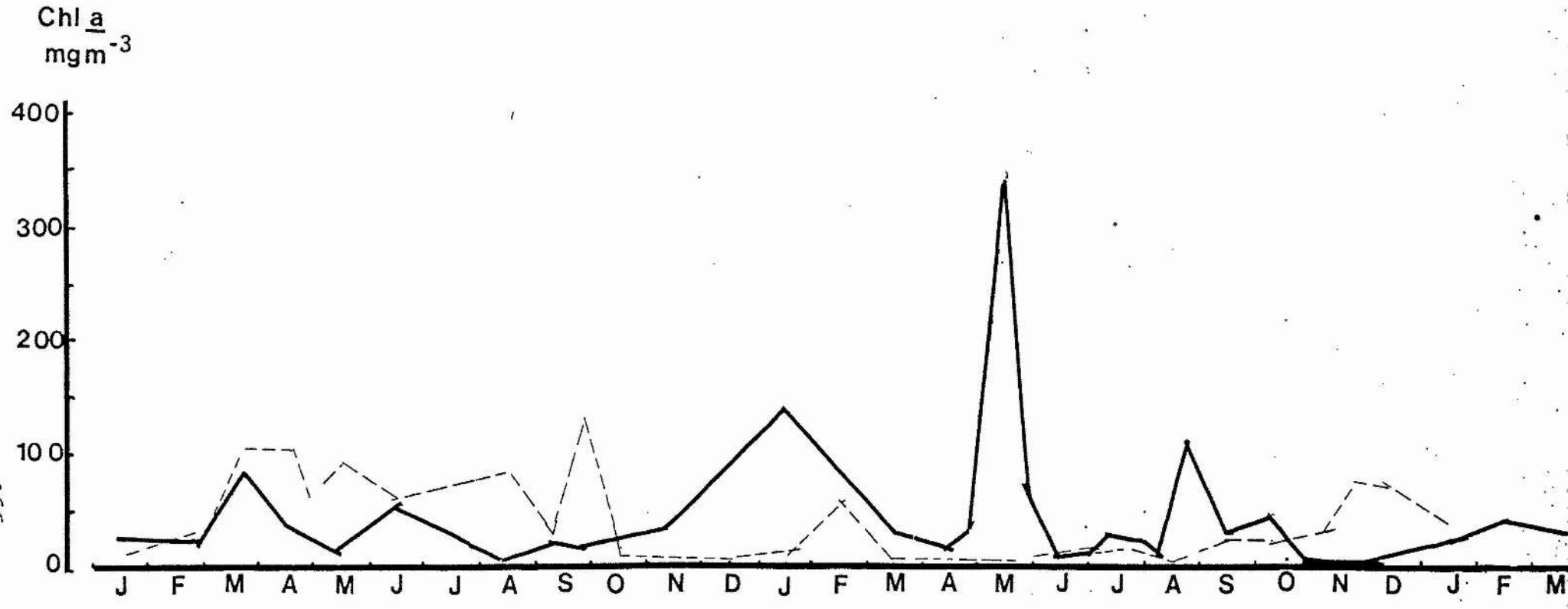

Chl a
mgm-3
400
300
200
100
0
J F M A M J J A S O N D J F M A M J J A S O N D J F M
Kil
Lin

FIG. 1:13

There was no characteristic stratification of phytoplankton chlorophyll a in either loch, although on several occasions there was a marked difference at 1.5 m in Loch Kilconquhar, Figure 1:14).

b) Submerged macrophytes

Practically no submerged macrophytes were observed in Loch Lindores during the study period. However, submerged macrophytes grew very well on the south west side of Loch Kilconquhar roughly near Station A, particularly after the decline of the Anabaena bloom in early July 1980. In September 1979, Cladophora fracta was growing very well and formed a dense mat on almost the entire south west shore (Figure 1:15). At no time in 1980 was there any sign of this plant but Enteromorpha intestinalis grew well at the same place, particularly at the depth of 0.75 m (Figure 1:16). In July 1980 Myriophyllum spicatum grew densely, reaching a maximum of 980 mg/m^2 chlorophyll a, and at the same time Zannichellia palustris was also growing very well (Figure 1:16).

c) Sedimentary chlorophyll

The concentrations of chlorophyll derived from the top layers of the loch sediments in Station B (Figure 1:17) clearly indicated that the overall value in Loch Lindores in the year 1979 was much higher than the value in Loch Kilconquhar.

TABLE 1:3

The seasonal dominant species of phytoplankton in Loch Lindores and Loch Kilconquhar.

Season	1979				1980				1981	
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Loch Lindores	Asterionella		Anabaena	Chlorella	Asterionella		Synedra	Ankistro-dismus	Asterionella	
Loch Kilconquhar	Stephanodiscus		Anabaena	Cladophora	Stephanodiscus		Anabaena	Aphanizo-menon	Stephanodiscus	

FIGURE 1:14

(opposite)

The chlorophyll a mg/m^3 stratification at Station B of a) Loch Lindores and b) Loch Kilconquhar in the year 1979.

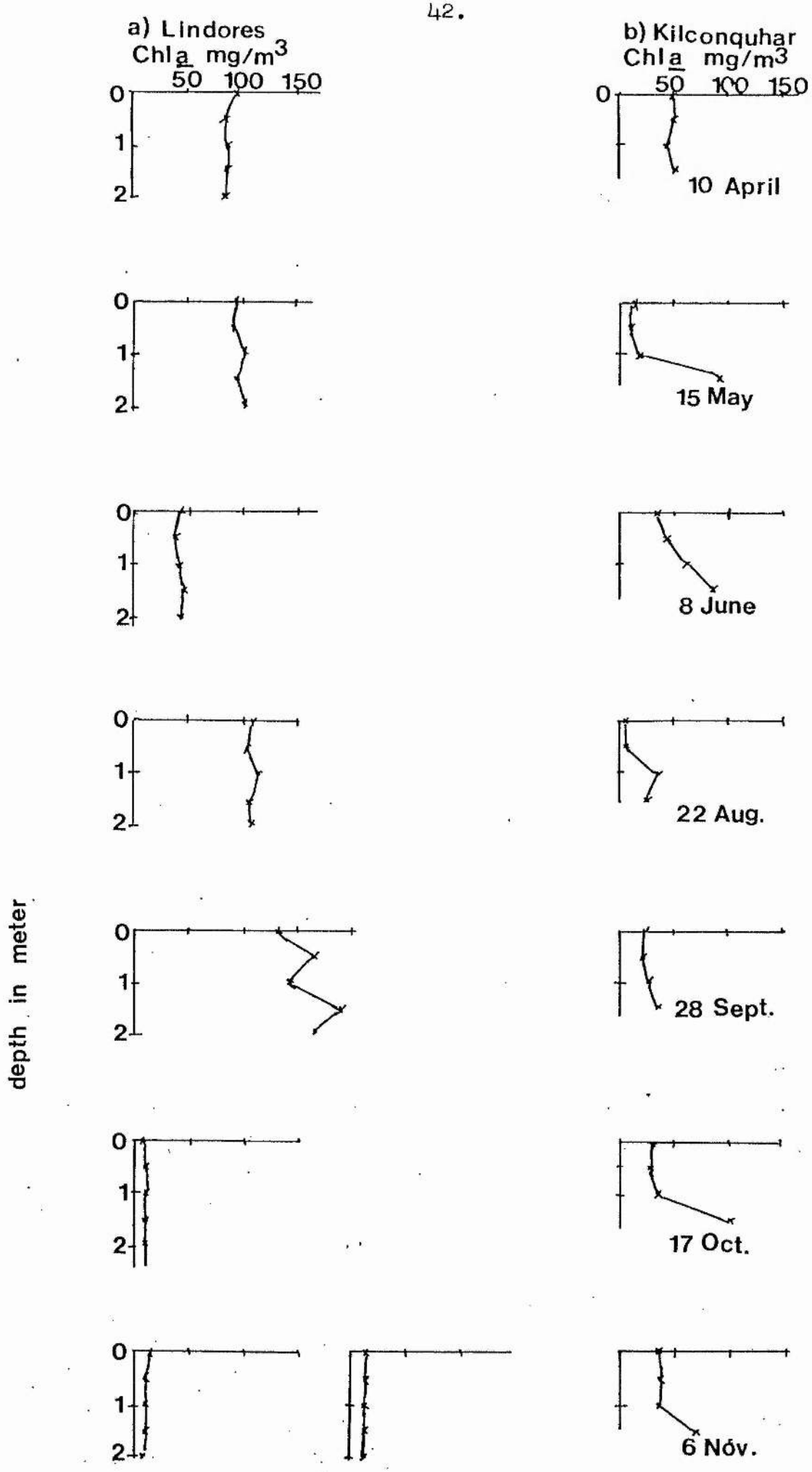

a) Lindores
Chl a mg/m3
50 100 150
b) Kilconquhar
Chl a mg/m3
50 100 150
0
1
2
10 April
15 May
8 June
22 Aug.
28 Sept.
17 Oct.
6 Nóv.
depth in meter

FIG.1:14

1979

FIGURE 1:15

(opposite)

The submerged macrophytes, predominently Cladophora, collected at Station A of Loch Kilconquhar in the year 1979.

FIG. 1:15

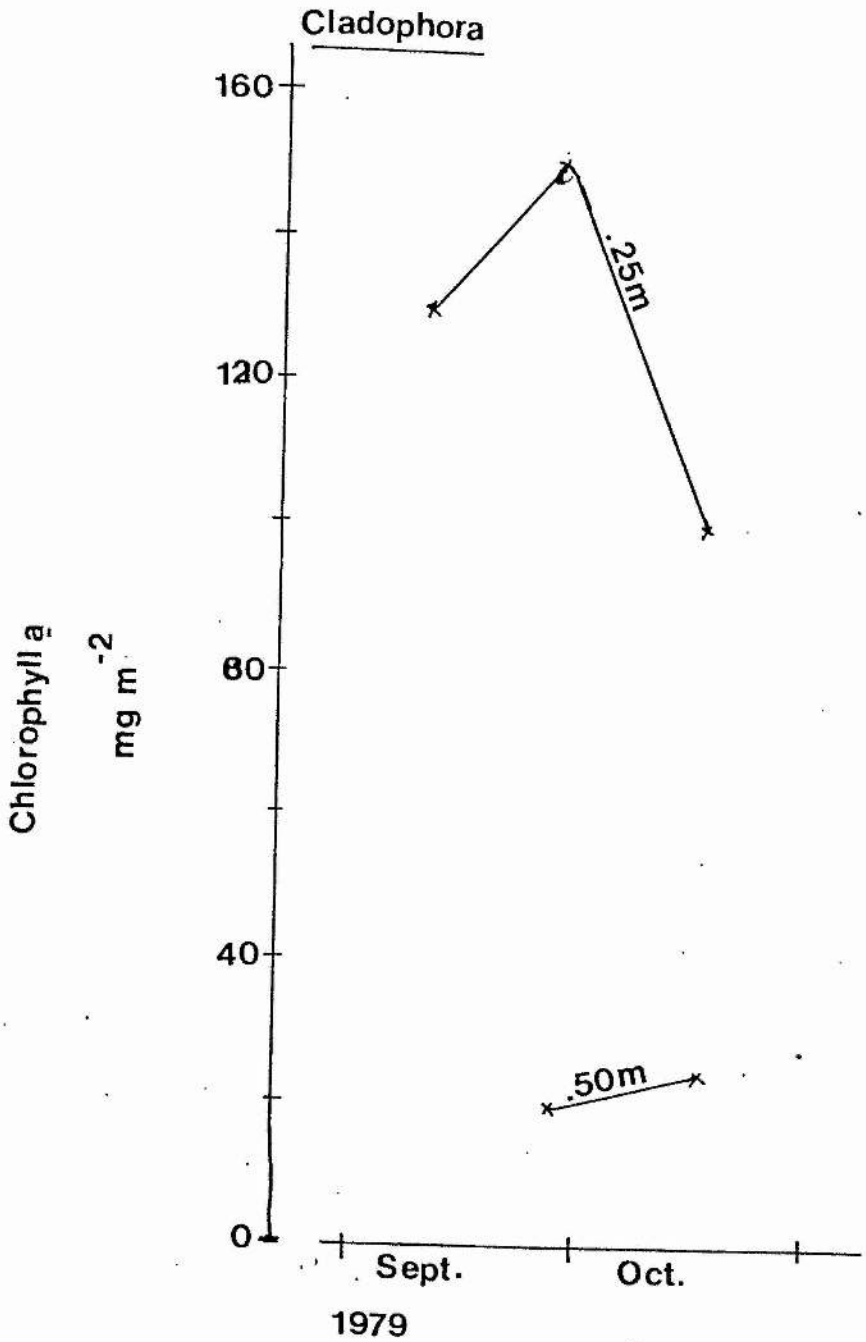

Cladophora
160
120
80
40
0
Chlorophyll a
mg m -2
.25m
.50m
Sept.
Oct.
1979

FIGURE 1:16

(opposite)

The submerged macrophytes at the depth of a) 0.25 m, b) 0.5 m and c) 0.75 m in Loch Kilconquhar in the year 1980.

FIG. 1:16

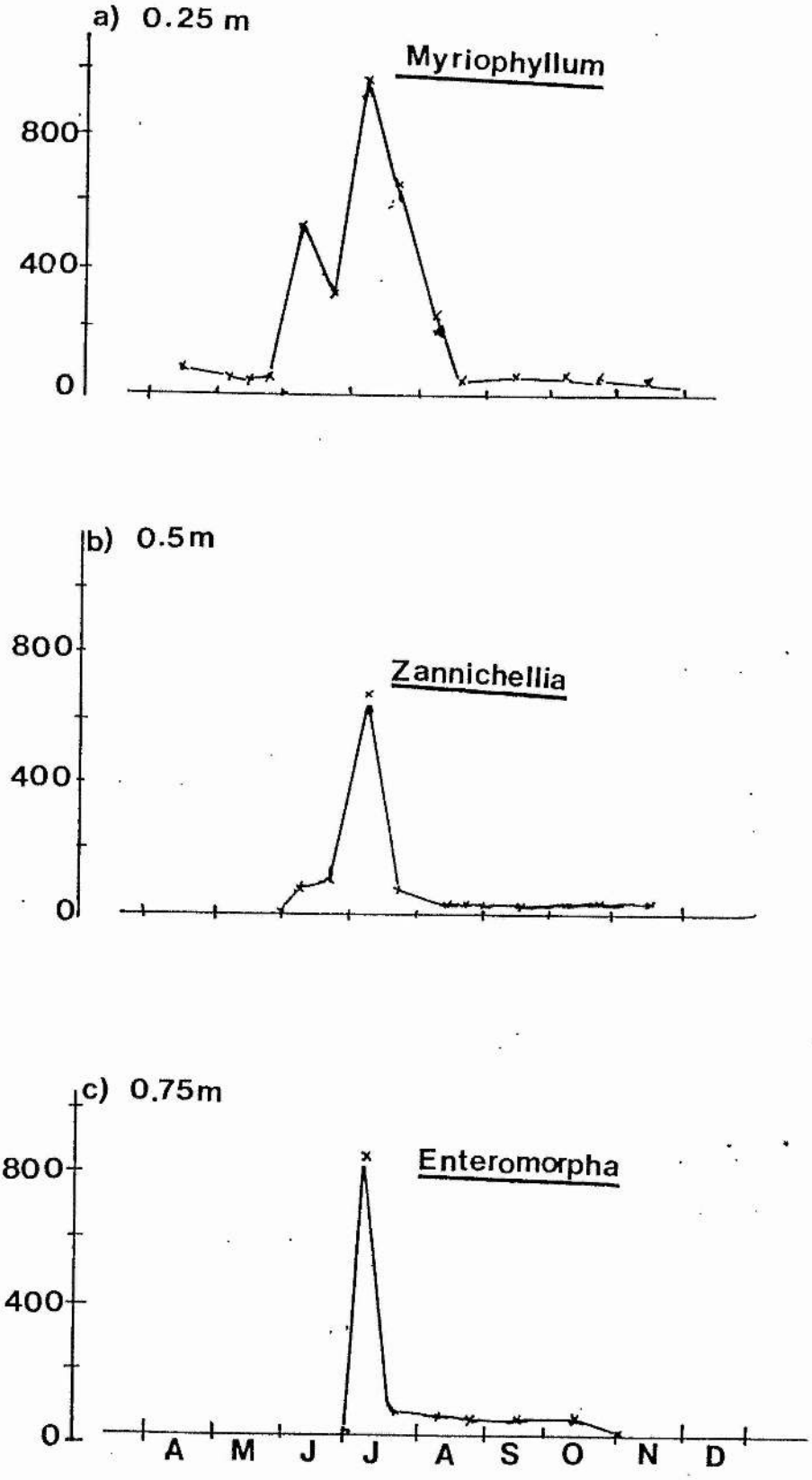
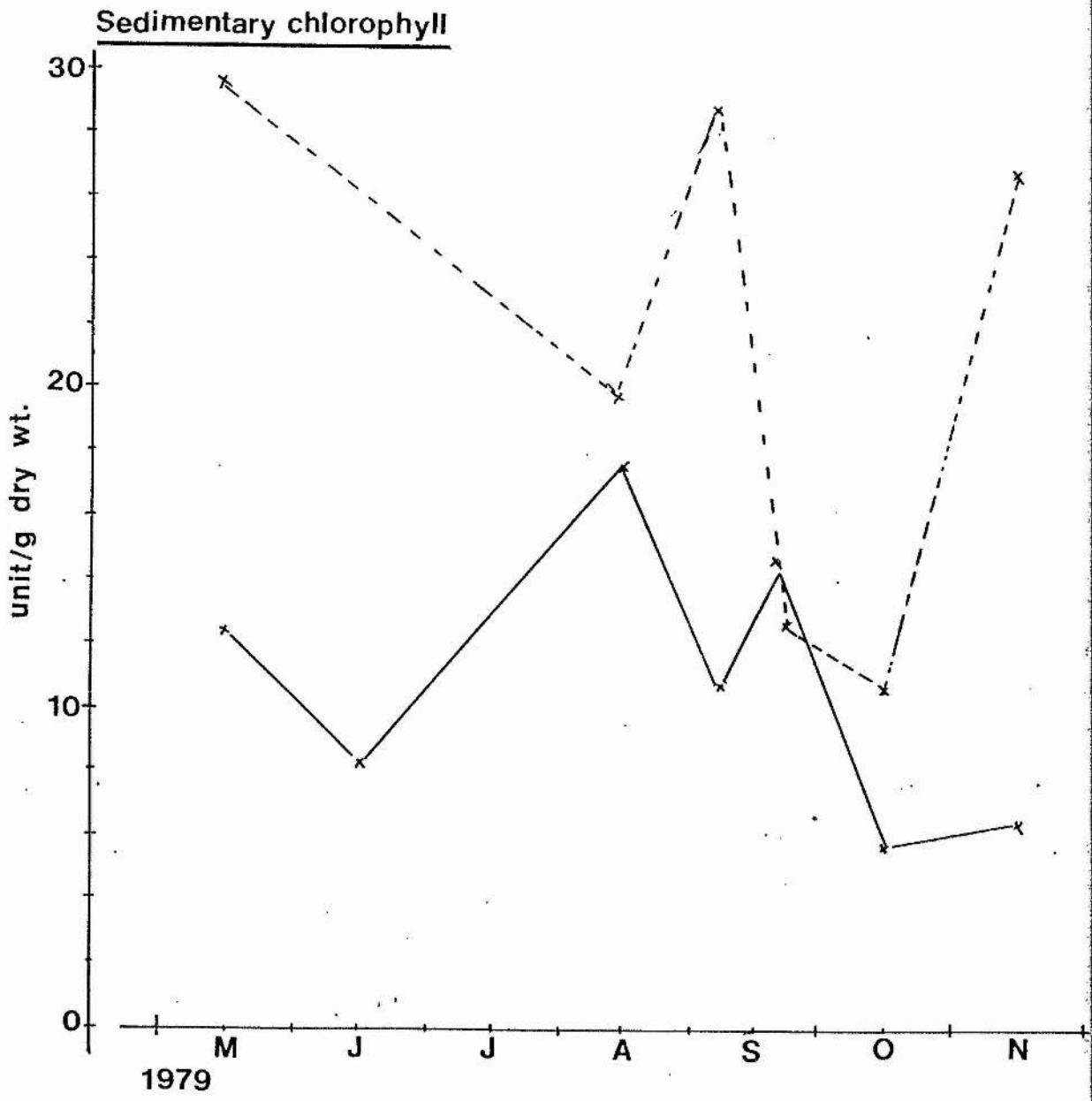

a) 0.25 m
Myriophyllum
800
400
0
b) 0.5m
Zannichellia
800
400
0
c) 0.75m
Enteromorpha
800
400
0
A
M
J
J
A
S
O
N
D

FIGURE 1:17

(opposite)

The seasonal changes in sedimentary chlorophyll at Station B for Loch Lindores (------) and Loch Kilconquhar (———) in the year 1979.

FIG. 1.17


Sedimentary chlorophyll
30
20
10
0
unit/g dry wt.
M
J
J
A
S
O
N
1979

I. 3) DISCUSSION

It became apparent after two years of the comparative study between these two eutrophic lochs that various factors such as soluble phosphate concentration, conductivity and alkalinity differed in their overall values. However, factors like soluble nitrate concentration, dissolved silica concentration and pH were rather similar (Table 1:4).

The seasonal changes in water chemistry and also phytoplanktonic chlorophyll a were observed to be considerably different between the year 1979 and the year 1980 in both lochs.

Based on this, it is divided into eight seasonal phases over two years of studied periods: a) Spring 1979; b) Summer 1979; c) Autumn 1979; d) Winter 1979-80; e) Spring 1980; f) Summer 1980; i) Autumn 1980 and j) Winter 1980-1981.

a) Spring 1979: In Loch Lindores, the chlorophyll a was generally above 100 mg/m^3. This was largely attributed to the Asterionella formosa bloom and at the same time, dissolved silica had become temporarily limited. Most possibly the increase in light duration and intensity, and also to a certain extent water temperature, stimulated rapid division in the already present winter population of this species. According to Lee (1980) Asterionella formosa is a common freshwater planktonic diatom that forms large spring growth, because during winter light and temperature limit the growth of this diatom. However, when the dissolved silica becomes limiting and reaches 0.5 mg/l, the diatom cease growth. At this time the chlorophyll a was moderately low in Loch Kilconquhar and the algae were mainly diatom, such as

Table 1:4

Limnological parameters in Loch Lindores and Loch Kilconquhar. The range of readings were taken over a two-year period, from February 1979 to March 1981

	Loch Lindores	Loch Kilconquhar
(SiO_2-Si) mg l^{-}	0.016 - 4.125	0.010 - 3.690
(NO_3-N) mg l^{-}	0.300 - 3.300	0.980 - 2.350
(PO_4-P) mg l^{-}	<0.001 - 0.112	0.004 - 0.780
Conductivity umhos	180 - 290	400 - 580
Alkalinity meg l^{-}	0.75 - 1.97	2.13 - 3.92
pH	7.30 - 9.20	7.60 - 10.40
Chlorophyll a (phytoplankton) mg m^{-3}	5.77 - 134.10	2.21 - 357.20

Stephanodiscus sp, Navicula sp and Synedra sp.

b) Summer 1979: The massive Anabaena bloom was observed in the late summer in Loch Lindores. On the other hand, the same bloom occurred much earlier in Loch Kilconquhar. As expected, the blue green algae normally appear in most of the eutrophic lochs in the temperate countries, particularly when the conditions become favourable . Brook (1964) came to the same conclusion regarding this bloom in which he stated that generally the shallow lochs of flurio glacial deposit origin particularly in the agricultural lowland area of Scotland often show water blooms in summer and autumn.

c) Autumn 1979: The massive Anabaena bloom was still persistent in Loch Lindores at the early part of Autumn. Subsequently after the bloom subsided, the chlorophyll a dropped tremendously to a minimum level of 15 mg/m^3 chl a. In Loch Kilconquhar the chlorophyll a was considerably low at this time. However, there was a massive growth of Cladophora fracta, particularly on the south east shore of the loch. According to Charles P. Mason (1965) that Cladophora occurs in the alkaline water and high pH. Whitford and Schumacher (1973) added that it generally occurs in freshwater habitats near the seashore.

d) Winter 1979-1980: At this time the chlorophyll a value was moderately low in Loch Lindores, except for a slight increase in February 1980. This was due to the dense growth of Asterionella formosa. On the other hand, there was a bloom

of Stephanodiscus sp. in Loch Kilconquhar where chlorophyll a reached 140 mg/m^3 in January 1980. This is probably due to the ample supplies of nutrients, particularly phosphate, in the water during the autumn sediment release. Even though the water was below 4°C and most of the loch intermittently frozen, this diatom still persisted. It should be noted that Bailey-Watts (1978) who had made a nine-year study of phytoplankton in Loch Leven also indicated that Stephanodiscus astraea Kütz and Cyclotella glomerata appeared to be the main component of the 1973-1974 mid-winter maximum of approximately 150,000 cell ml^{-}.

e) Spring 1980: The chlorophyll a was generally very low at this time in Loch Lindores. On the other hand, there was an early appearance of Anabaena bloom in Loch Kilconquhar, in late spring. According to Reynolds and Walsby (1975) in temperate regions, there is often a characteristically seasonal development of bloom-forming algae in which filamentous forms such as Anabaena flos-aquae appear first between April and July. This species begins to grow above 5°C, producing its most rapid rate of increase between 10°C and 15°C. So it is not surprising that, in this case, it had appeared much earlier while the water temperature was still moderately low.

f) Summer 1980: There was no sign of blue green algae in Loch Lindores. Although the water temperature was fairly warm, the chlorophyll a reading was very low. On the other hand, there was a second appearance of a blue green bloom

in Loch Kilconquhar, but this time it was Aphanizomenon flos-aquae, where it reached a maximum of 130 mg/m^3 chlorophyll a, in late August. It seems that soluble nitrate increases slightly in Loch Kilconquhar water at the time of the bloom. Similar results were obtained by Horne et al. (1979) in which he observed in Clear Lake that during the massive bloom of Aphanizomenon flos-aquae, the lake's nitrogen income had doubled.

g) Autumn 1980: At this time of the year both of the lochs were generally low in phytoplanktonic chlorophyll a.

h) Winter 1980-81: Only in late winter and early spring was Asterionella formosa observed to come out in Loch Lindores. Unlike the previous winter the chlorophyll a in Loch Kilconquhar was moderately low.

These facts illustrate how difficult it is to predict the sequence of events, particularly the occurrence of blue green algal blooms, that take place in an enriched loch. In a review Oswalt and Bermann (1977) concluded that after one hundred years of observation and experiment by limnologists, the causes of dominance by certain algae and frequency of algal blooms are not fully understood, particularly in the freshwater environment. However, as stated previously many limnologists such as Vollenweider (1970), Dillon and Rigley (1974) and Schindler (1978) argue strongly that the most significant factor in controlling phytoplankton productivity, particularly that of blue green algae is phosphate. This appears with the main conclusion that can be drawn from data

present here.

The most obvious feature in Loch Lindores, particularly in the year 1980, was the absence of a blue green algal bloom. At the same time the overall soluble phosphate concentration was low and indicates that this was insufficient to initiate the growth of such blooms. Although the loch was considered at the outset likely to be influenced by agricultural run-off, the inflow sample from the arable land taken on 17th October, 1979, was low in phosphate. However, the nitrate concentration in the same inflow was extremely high, reaching 6.20 mg/l NO_3-N. Thus much nitrogenous fertilizer was reaching the loch.

Furthermore, according to Armitage (1974) phosphate, unlike nitrate, is virtually immobile in the soil and therefore is not easily leaked out. Many workers pointed out that the presence of soluble phosphate in the water is quickly utilized by the phytoplankton or it could precipitate in loch sediment.

Regarding precipitation of phosphate with other chemical elements Kucera (1976) clearly indicated that calcium phosphate is formed when the environment is alkaline and under more acid conditions, phosphate enters into chemical combination with iron and aluminium. In this case, unless there is an adequate supply of phosphate from the loch sediment, its concentration will subsequently become limited in the loch water. Generally in warm weather where there is high biological demand for dissolved oxygen, particularly on the mud surface, anaerobic conditions may develop under stratification conditions and these should subsequently lead to nutrient

release.

However, in Loch Lindores, presumably with little biological demand for oxygen or with no strong stratification, there is no severe depletion of dissolved oxygen even in summer. As a result, there is possibly no sediment release.

As stated before, the soluble phosphate concentration in Loch Kilconquhar was, in general, exceptionally high. According to Round (1973) soluble phosphate is generally present in small quantity in natural water, except in some which are polluted by certain organic materials. Like Loch Lindores, the inflow which drains from the adjoining agricultural area was reasonably low in soluble phosphate. By contrast, the loch was extremely high in soluble phosphate especially in summer. Perhaps sediment release had occurred. In addition, the presence of many birds on a relatively small loch like Loch Kilconquhar will obviously have a tremendous impact on the loch ecosystem itself, particularly regarding concentrations of nutrients such as phosphate.

This particular question of phosphate supply is of a great interest especially in the ecological context of freshwater lakes so it will be thoroughly dealt with in the following chapters.

Nitrate is an equally important plant nutrient. There are ample supplies of nitrate from the agricultural inflows to both lochs. In addition, blue green algae such as Anabaena flos-aquae which normally occur in summer, can synthesize atmospheric nitrogen into usable nitrate, some of which may eventually be utilized by other algae, as pointed out by Horne (1979). Hence, it seems likely that the amount of nitrate available is sufficient to maintain algal and macrophyte growth (Table 1:5).

Table 1:5

The range of PO_4-P and NO_3-N concentrations in enriched and unenriched lakes.

Lake	PO_4-P mg/l	NO_3-N mg/l	Brief account	Reference
Vellore Moat (Madras, India)	2.80-22.00	undectable (High in NH_4-N)	enriched by faecal pollution	Sveenivasan (1972)
Hickling Broad (Norfolk, England)	<0.001-0.36	<0.001-2.20	enriched by gull droppings and agricultural run off	Leah (1978)
Lake Sammamish (U.S.A.)	<0.001-0.014	<0.001-0.50	unenriched lake	Birch (1981)
Loch Lindores (Fife, Scotland)	<0.001-0.112	0.30-3.30	enriched by agricultrual run off	1981 (This thesis)
Loch Kilconquhar (Fife, Scotland)	0.004-0.78	0.98-2.35	enriched by bird droppings and agricultural run off	1981 (This thesis)

As described by Rockwell et al. (1980), Thomann and Segna (1980) and Clegg (1965), silica is only important for diatom growth. In both lochs, the dissolved silica concentration was generally low during the dense growth of Asterionella formosa in Loch Lindores and likewise Stephanodiscus sp. in Loch Kilconquhar. Apart from this, it seemed that sufficient amounts were present to be limiting the diatom growth in both lochs.

Bagley and William (1973) stated that pH has been over-emphasized as an ecological factor but this does not mean that it is not worthy of measurement. It frequently does give a clue to the existence of other factors that may be highly significant. For example, highly polluted water has either too low or too high pH value. It seems that both the lochs studied have pH values not too alkaline except on occasion in Loch Kilconquhar during the peak of Anabaena flos-aquae bloom in early summer 1980 where it reached a maximum value of 10.2.

This is most probably due to the highly utilized free CO_2 and HCO_3 in the water at that time by this species. Since, according to Allen and Spence (1981) when the alkalinity and carbon concentration are known, the photosynthetic activity of microalgae can be measured by the change in pH. They concluded from 4 microalgae and 10 macrophytes studied that the microalgae (including Anabaena flos-aquae) had considerably greater apparent affinities for HCO_3^- and slightly greater apparent affinities for CO_2 than the macrophytes.

It should be noted that the conductivity of Loch Kilconquhar was also extremely high. This is due to the

high concentrations of dissolved salt. A similar result was observed in Lake Maggiore, North Italy, in which according to Bonomi (1968) over a period of nine years, the conductivity increased by about 10%, which implies a corresponding increase in the quantity of dissolved salts, and a large increase, about 20%, in the amount of soluble nitrate.

According to Vallentyne (1955) sedimentary chlorophyll is not only derived from the macrophytes and microalgae in the lake, but also from plants' remains washed into the lake basin. Gorham (1960) stressed that the concentration of chlorophyll derived mainly from benthic algae can be considered a sensitive index of lake fertility. Table 1:6 shows that sedimentary chlorophyll in Loch Lindores was higher than in Loch Kilconquhar. However, in terms of their sedimentary chlorophyll, both lochs are considered very fertile compared with most lakes in the Lake District.

From the light readings it is clearly indicated that light could at times penetrate to the very bottom of either of these two shallow lochs. Apart from the shading effect by the phytoplanktonic blooms, the difference between the slopes may be due to differences in non-algal particulate and dissolved substances in both lochs (Bindloss 1974). This may also explain the scatter of the points at low chlorophyll a concentrations in Loch Kilconquhar.

Several submerged macrophytes, such as Potamogeton praelongus, Nitella sp. and Chara sp. were encountered previously by Spence (1964) in Loch Lindores. It was quite strange that no submerged macrophytes were found in this loch during the studied period. According to Spence (Pers. comm.)

Table 1:6

Sedimentary chlorophyll derivatives from various lakes. (mean value)

Lake	Sedimentary chlorophyll unit per g dry weight	Reference
Westwater	0.21	Gorham (1960)
Ennerdale Water	0.24	Gorham (1960)
Windermere, North basin	0.83	Gorham (1960)
Esthwaite Water	1.37	Gorham (1960)
Priest Pot	6.88	Gorham (1960)
Loch Kilconquhar	9.46	1981 (this study)
Loch Lindores	22.12	1981 (this study)

perhaps the intensive use of banned herbicides (weed killer) in the early sixties, which eventually reached the loch, destroyed the submerged macrophytes. This may be one of the reasons why there are now very few submerged macrophytes in the loch.

On the other hand, various submerged macrophytes, such as Enteromorpha intestinalis, Zannichellia palustris, Cladophora fracta and Myriophyllum spicatum were found abundantly in Loch Kilconquhar, particularly in summer 1980.

1. 4) CONCLUSION

The results clearly indicate that both lochs are non-stratified and that Loch Kilconquhar is highly eutrophicated. Phosphate seems to be the key factor for lake eutrophication. The absence of a blue-green algal bloom in the year 1980 in Loch Lindores strongly suggests that with proper phosphate control measures, this type of algal bloom can be prevented.

This, of course, does not mean that other elements are not important to phytoplankton, particularly the blue-green algae, but only that these elements are present in excess quantities relative to phosphate in the loch water; for example, both lochs get an ample supply of nitrate from agricultural run-off. Algal abundance, therefore, generally varies with the amount of phosphate available in water.

While blue-green algal blooms may be undesirable, present results suggest that these blooms contribute to the nitrogen budget of both lochs.

Present data indicate that excess nutrients in the water only result in blue-green algal growth in warm conditions. Thus, in Loch Kilconquhar, blue-green algae showed a marked response to high available phosphate in the water, particularly during the rise of water temperature in late spring, but excess nutrients in the water under cold conditions favoured diatom growth.

It seems that most of the basins of both lochs lie within the euphotic zone, which, with sufficient supply of nutrients in loch water and sediment, allowed high productivity of benthic algae and, in the shallowest parts of Loch Kilconquhar,

submerged macrophytes. Submerged macrophytes are scarce in Loch Lindores but sedimentary algae grow well in that loch and, therefore, contribute to the overall productivity of this loch.

CHAPTER II

SOURCES OF NUTRIENTS, PARTICULARLY PHOSPHATE IN LOCH KILCONQUHAR

2. 1) AIMS AND METHODS

Loch Kilconquhar was chosen for a further intensive study because of the relatively high soluble phosphate concentration in the loch water. Since phosphate is the most essential nutrient governing the loch's productivity, the possible sources of this nutrient in the loch are thoroughly investigated. Besides phosphate, nitrate and silica are also analysed.

Presumably the duck and the gull droppings accounted for nearly 90% of the total bird droppings in Loch Kilconquhar. As stated earlier, the chemical composition of their droppings depends on food intake; most of the duck species consume mainly vegetative material, while the gulls scavenge fish scraps and occasionally worms. These facts strongly suggested that their droppings would have different concentrations of bulk phosphate and nitrate. To have some idea about this, one gram fresh sample each of duck and gull droppings were analysed for total phosphate and total kjeldahl nitrogen concentrations. In addition, the solubility of samples of each type of dropping in distilled water was also studied.

The release of nutrients from decaying submerged macrophytes and from a decaying Aphanizomenon bloom, was also looked into.

A) Field

As stated before, the inflow is situated on the east side of the loch and drained from approximately 200 acres

of arable land. The agricultural run-off which is presumably rich in nutrients, particularly nitrate and phosphate, could be one of the major sources of nutrients in the lake water. In order to investigate this possible nutrient source for the loch, routine water samples from the inflow were collected and analysed almost every fortnight, from 11th March, 1980 to 10th March, 1981. At the same time, water samples were taken from Station A, Station B and also from the outflow which is situated on the south side of the loch (see Map 2).

Birds

To get a precise estimate of the bird population in this loch is relatively difficult. However the bird numbers were estimated on every visit and observations were made from the regular points along the shore, including Station B (see Map 2). A pair of Chinon countryman binoculars which magnified 50 times were used to identify the bird species. The species were then classified into three major families found in the loch, notably Anatidae (the duck family), Rallidae (the coot family) and Laridae (the gull family).

The duck droppings were normally collected near the nests, amongst the bushes. As gulls do not roost on the shore at Kilconquhar and they defaecate in the water, droppings had to be collected from the harbour at Elie, one km away. It is assumed that these droppings are qualitatively similar to those droppings in the loch itself.

Water analysis

The water samples from the inflow, the open loch

(Station A and Station B) and the outflow, were filtered through a 0.45 um membrane filter. The filtrate was then analysed for dissolved silica (SiO_2-Si), soluble nitrate-nitrogen (NO_3-N) and soluble reactive phosphate (PO_4-P). The methods used for these nutrient analyses were described previously in Chapter 1. The total phosphate and the total kjeldahl nitrogen concentrations were analysed from the unfiltered water samples, and the analytical methods have also been described previously.

The methods for estimating phytoplanktonic chlorophyll a, submerged macrophytes (chlorophyll a) and sedimentary chlorophyll have also been extensively described in the previous chapter. Basically, cold acetone was used to dissolve the chlorophyll from the various kinds of plant material and the chlorophyll densities were read spectrophotometrically at certain wavelengths.

Laboratory experiments

Experiment 1:

Bird droppings: one gram of fresh duck dropping and also one gram of fresh gull dropping were each placed in separate 50 ml kjeldahl flasks. To each sample was added 5 ml of nitrogen free sulphuric acid and each sample was gently heated on the mantle. When the dropping charred, a special kjeldahl catalyst tablet was dropped into the flask. It was further heated until white fumes evolved and a clear solution was obtained. The solution was then neutralized with sodium hydroxide and subsequently transferred to a 50 ml volumetric flask to which distilled water was added

until the volume became 50 ml. The experiment with each type of bird dropping was replicated five times. This method is almost the same as the sediment digestion which was based on Slater and Boag (1978).

Ten ml of the subsample was used to analyse total phosphate which was based on Harwood (1970) and about 5 ml of the clear solution was analysed directly for total kjeldahl nitrogen in the spectrophotometer using 220 nm (uv) ultra violet light.

Experiment 2:

To compare the rate of solubility of the duck and the gull droppings, one gram of each of these droppings were analysed for their soluble phosphate concentrations. Each sample was placed in a 500 ml flask and then 250 ml of distilled water was added. Samples were virogously shaken and the initial readings for soluble phosphate concentrations were taken after one hour, but the other readings were taken at two hour intervals over a period of eight hours. The experiment with each dropping was replicated three times.

Experiment 3:

To observe the effect of loch sediment and duck dropping on the chemistry of the loch water, an experiment was conducted in a water bath at controlled temperature of 15°C. Loch Kilconquhar water collected on 29th January 1980 was used, where the values of soluble phosphate, soluble nitrate and dissolved silica concentrations were known. With this water as a standard, one gm of fresh sediment and one gm of

fresh duck dropping were used to estimate the absorptive properties of these substances.

The measured amounts of sediment and duck droppings were placed in a 75 ml test tube and 50 ml of loch water was then added and three replicate samples were run. The experiment was run for three days and each day subsamples were taken for analysis of soluble phosphate, soluble nitrate and dissolved silica concentrations. After each analysis, loch water was added to the test tubes so that the volume always remained 50 ml. Only one-fifth of the actual volume was used for each analysis.

Experiment 4:

Decaying submerged macrophytes and algal blooms can result in an increase of nutrients, particularly phosphate, in the water. Two species of submerged macrophytes found abundantly in Loch Kilconquhar, namely Myriophyllum spicatum and Cladophora fracta, were used.

Experiment 4a:

One gram of fresh Myriophyllum spicatum and Cladophora fracta were each placed in separate 500 ml flasks. To the flask was then added 250 ml of distilled water and its mouth was plugged with cottonwool. Subsequently the flask was covered with aluminium foil to avoid photosynthesis and was then placed in a water bath at a controlled temperature of 15°C. Each week, for seven weeks, a subsample of the water was analysed for soluble phosphate and soluble nitrate. To ensure the volume was always at 250 ml, distilled water was

added to the flasks after each analysis. Four replicated flasks for each species ware used.

Experiment 4b:

One litre of water taken from the outflow on 26th June, 1980 which contained concentrated phytoplankton crop mainly of Aphanizomenon (210.85 chl a mg m^{-3}) was used to observe the nutrient release from a common phytoplankton species. The initial nutrient concentrations of the water were measured and the natural water sample was placed in a two litre flask covered with aluminium foil. Subsequently the flask was placed in a water bath at a constant temperature of 15°C and kept for two weeks.

After a fortnight, the massive bloom had sedimented to the bottom and the water was siphoned to analyse the final soluble phosphate and soluble nitrate concentrations.

2. 2) RESULTS

The mean nutrient concentration from the integrated samples at Station A and Station B is shown in Table 2:1 and graphically in Figure 2:1. It should be noted that the integrated sample ($\overline{x}$) represents at least five samples ($n = 5$), on each sampling occasion. The dissolved silica concentration was generally high in summer and autumn, but extremely low in winter and spring. In late July 1980, the soluble nitrate concentration reached a maximum of 2.24 mg/l [NO_3-N] and the figure also shows that it was consistently high throughout the year. A sharp rise in soluble phosphate concentration to a maximum value of 0.641 mg/l [PO_4-P] was observed in late June 1980; however the concentrations were generally low after September 1980.

Figure 2:2 shows a possible correlation between the concentrations of soluble phosphate and soluble nitrate in Loch Kilconquhar. The readings were derived from 23 integrated soluble phosphate [PO_4-P] and soluble nitrate samples. Only 24% (100 x r^2%) of the variation in the values of the variable y (NO_3-N cons.) may be accounted for in the linear relationship with x (PO_4-P cons.).

Productivity

The overall integrated productivity is shown in Table 2:2. It should be noted that the integrated productivity (= mean value) represents at least three samples ($n = 3$) and the values are on a real basis. Figure 2:3 shows that

Table 2:1

The integrated nutrients samples for Loch Kilconquhar, from 11 March 1980 to 10 March 1981. Results are mean of five samples ± 95% CL (n = 5).

Date	SiO_2-Si mg l^{-1}	NO_3-N mg l^{-1}	PO_4 P mg l^{-1}
11 March 1980	0.066±0.023	1.400±0.038	0.172±0.009
13 April 1980	0.230±0.084	1.602±0.374	0.099±0.018
17 April 1980	0.104±0.075	1.384±0.025	0.252±0.019
1 May 1980	0.686±0.220	1.452±0.046	0.252±0.043
15 May 1980	1.545±0.361	1.938±0.374	0.176±0.011
29 May 1980	1.915±0.584	1.565±0.110	0.124±0.049
17 June 1980	2.720±0.011	1.600±0.012	0.180±0.002
26 June 1980	0.916±0.044	1.870±0.131	0.640±0.108
8 July 1980	3.240±0.025	1.913±0.057	0.468±0.046
23 July 1980	2.904±0.262	2.236±0.086	0.177±0.037
13 Aug. 1980	3.663±0.087	2.010±0.185	0.198±0.071
26 Aug. 1980	2.793±0.543	1.408±0.050	0.142±0.041
3 Sept. 1980	2.802±0.031	1.562±0.273	0.062±0.037
13 Oct. 1980	3.654±0.069	1.566±0.046	0.041±0.009
22 Oct. 1980	3.328±0.049	1.398±0.025	0.024±0.003
5 Nov. 1980	0.228±0.014	1.482±0.059	0.022±0.002
18 Nov. 1980	0.120±0.001	1.250±0.001	0.074±0.001
3 Dec. 1980	1.322±0.073	1.370±0.217	0.019±0.007
17 Dec. 1980	0.154±0.001	1.607±0.001	0.049±0.008
14 Jan. 1981	0.238±0.005	1.470±0.016	0.042±0.007
30 Jan. 1981	1.784±0.023	1.164±0.032	0.015±0.001
18 Feb. 1981	1.200±0.009	1.100±0.009	0.004±0.001
10 March 1981	1.764±0.050	1.036±0.029	0.007±0.002

FIGURE 2:1

(opposite)

The integrated (SiO_2-Si), (NO_3-N) and (PO_4-P) concentrations derived from Table 2:1. Results are mean of at least five samples $\pm$ 95% CL (n = 5).

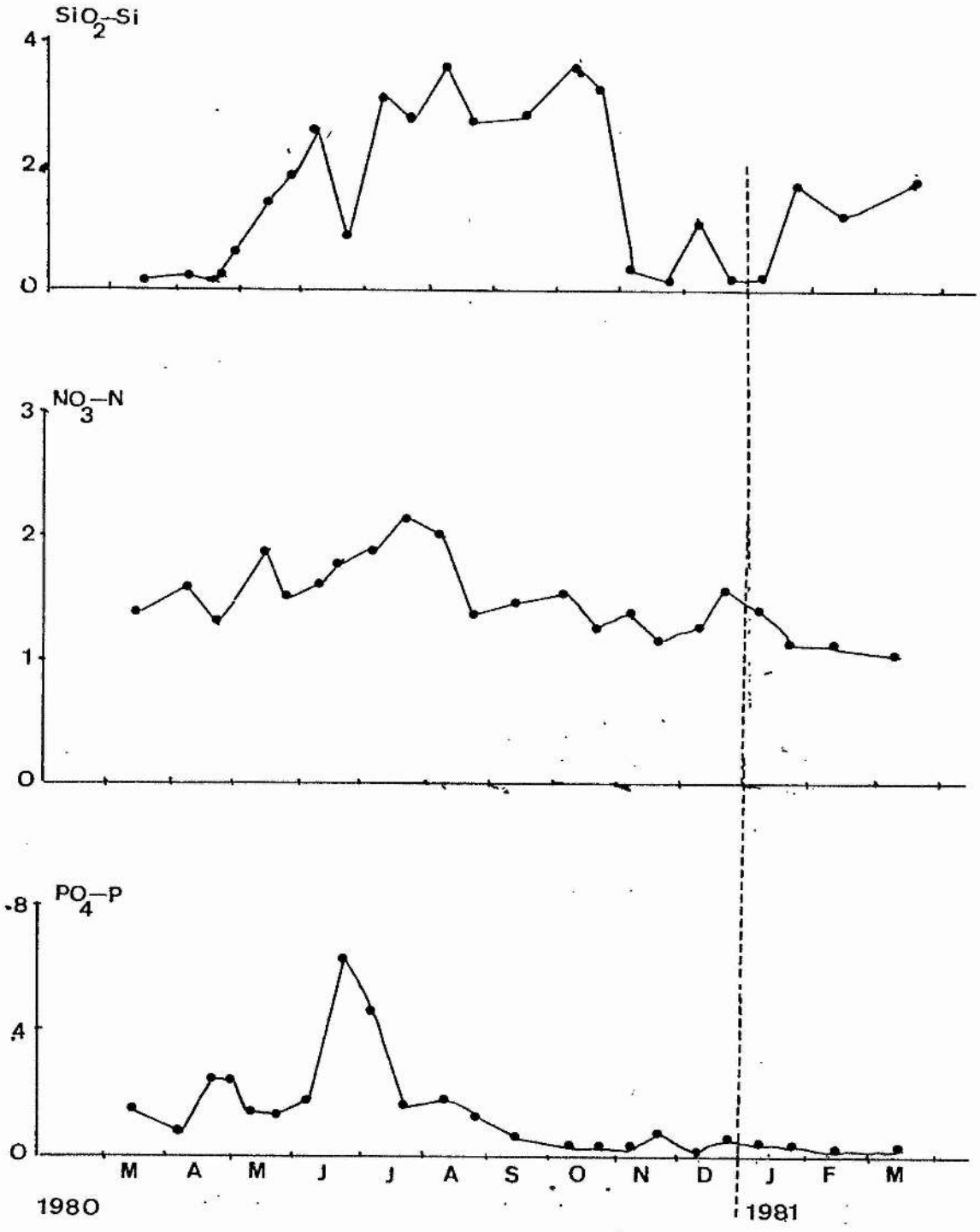


FIG. 2:1

Table 2:2

The overall integrated productivities for Loch Kilconquhar: a) mean phytoplanktonic chlorophyll a ± 95% CL (n = 5); b) mean submerged macrophytes ± 95% CL (n = 3); c) mean aedimentary chlorophyll ± 95% CL (n = 3); from 11 March 1980 to 10 March 1981.

Date	Phytoplanktonic productivity chlorophyll a mg m^{-2}	Submerged macrophyte chlorophyll a mg m^{-2}	Sedimentary chlorophyll mg m^{-2}
11 March 1980	51.25± 9.32	-	7.26±2.19
2 April 1980	52.54± 7.14	-	7.32±0.71
17 April 1980	37.15±10.52	63.00±19.25	9.38±0.45
1 May 1980	103.71±30.21	40.00±21.00	13.96±2.04
15 May 1980	461.84±47.02	28.00±15.75	5.48±0.28
29 May 1980	182.47±40.05	26.00± 7.88	5.06±0.85
17 June 1980	26.84±00.01	299.00±102.38	-
25 June 1980	45.95±10.52	189.00±56.88	7.38±1.47
9 July 1980	52.19± 7.16	845.00±52.50	11.76±1.11
23 July 1980	40.32±10.12	255.00±44.18	-
13 Aug. 1980	39.07± 9.10	83.00±18.13	8.31±0.84
26 Aug. 1980	67.72±16.66	16.00± 5.67	10.86±0.59
3 Sept. 1980	69.01±14.39	21.00± 5.67	9.39±0.22
13 Oct. 1980	30.04± 9.14	32.00±13.60	7.59±0.61
22 Oct. 1980	34.33± 6.66	10.00± 5.00	8.52±1.70
5 Nov. 1980	22.17± 4.18	3.00± 0.54	5.59±0.91
18 Nov. 1980	4.42± 1.02	-	-
6 Dec. 1980	12.17± 2.53	-	4.63±1.13
17 Dec. 1980	59.67± 0.02	-	-
14 Jan. 1981	87.70± 8.80	-	-
30 Jan. 1981	100.84± 2.92	-	8.32±1.29
18 Feb. 1981	88.34± 2.14	-	-
10 March 1981	61.32± 8.65	-	7.86±0.19

FIGURE 2:2

(opposite)

A possible correlation between integrated (PO_4-P) upon (NO_3-N) for Loch Kilconquhar. The straight line represents regression equation ($y = 1.135\ x + 1.364$; $r = 0.156$).

FIG. 2:2

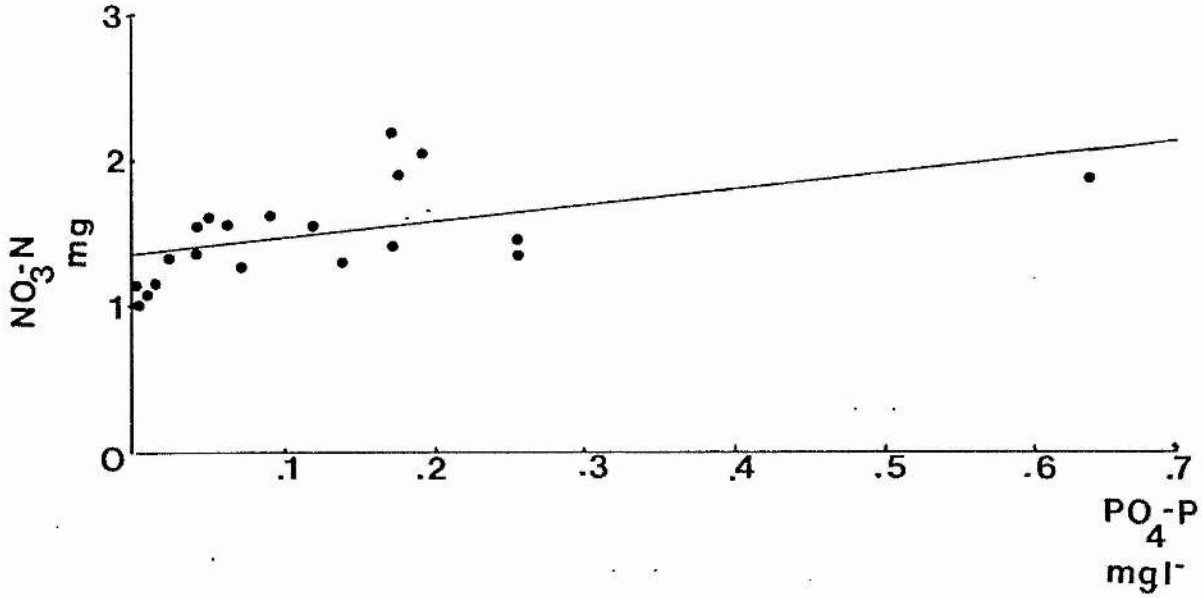
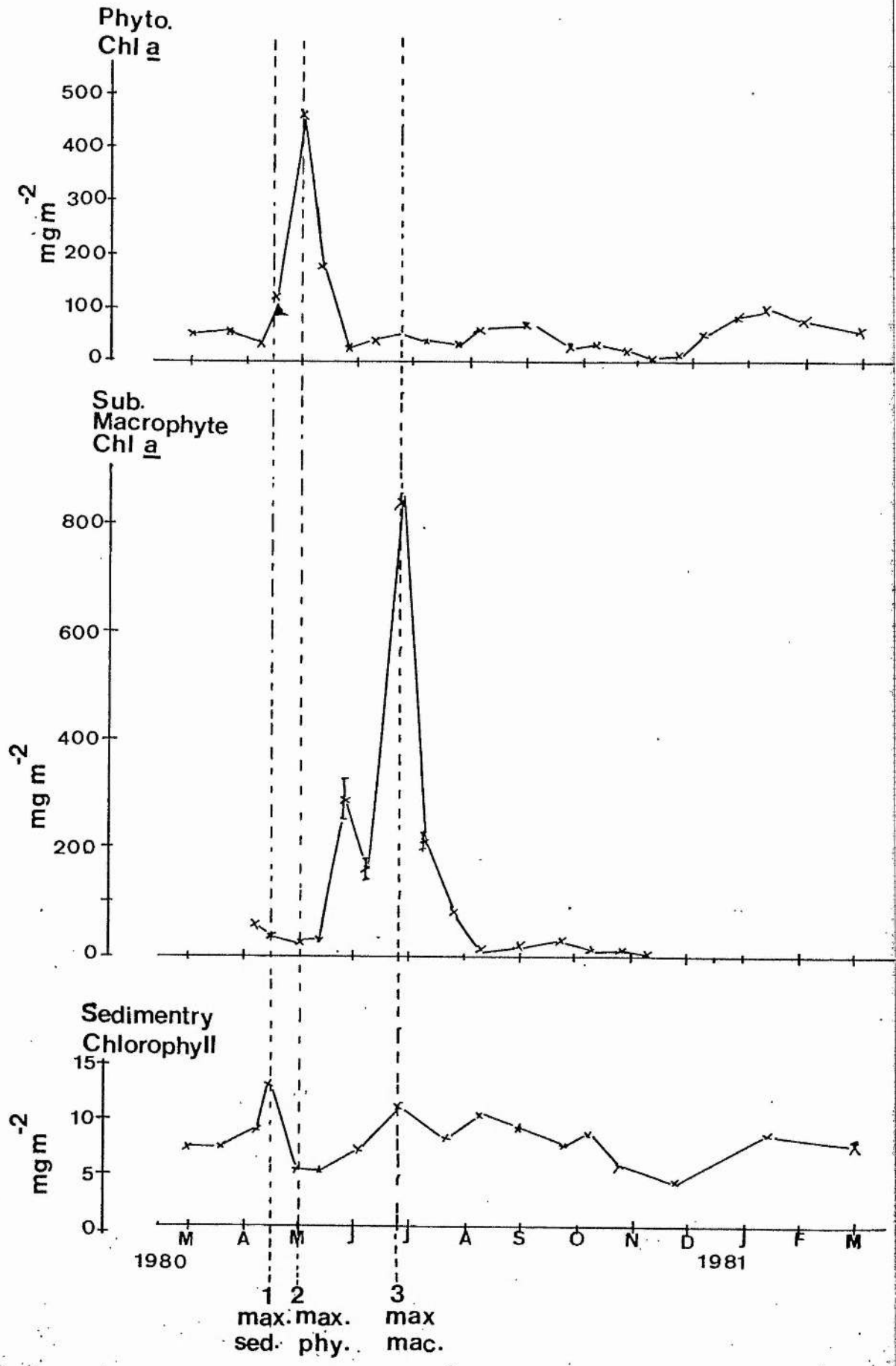


FIGURE 2:3

(opposite)

The overall integrated productivities for Loch Kilconquhar from 11 March 1980 to 10 March 1981, showing also 1) max. sedimentary chlorophyll in April, 2) max. phytoplanktonic chlorophyll a (*Anabaena* bloom) in May and 3) max. submerged macrophytes in late June. (mean values ± 95% CL).

FIG. 2:3


Phyto.
Chl a
500
400
300
200
100
0
mg m -2
Sub.
Macrophyte
Chl a
800
600
400
200
0
mg m -2
Sedimentry
Chlorophyll
15
10
5
0
mg m -2
M A M J J A S O N D J F M
1980
1981
1 max. sed.
2 max. phy.
3 max mac.

sedimentary chlorophyll reached a maximum value of 13.96 ± 2.04 mg m^{-2} in early May 1980, followed by phytoplanktonic chlorophyll a which consists mainly of Anabaena flos-aquae and reached the maximum value of 461.84 ± 47.02 mg m^{-2} chlorophyll a in the middle of the month. After the phytoplanktonic bloom collpased, a massive growth of submerged macrophytes were observed in July 1980.

Table 2:3 shows the changes in cell (filament)/ml for the dominant phytoplankton species found in Loch Kilconquhar.

Sources of nutrients

The inflow

Table 2:4 shows the mean concentrations from the inflow (n = 22), the loch (n = 23) and the outflow (n = 22), while n represents the number of sampling occasions from 11 March 1980 to 10 March 1981.

Figure 2:4a shows that the mean soluble phosphate concentration over one year in the loch is about 7 times higher than the inflow. However, the value for the outflow is slightly lower than the loch water. On the other hand, the soluble nitrate concentration over the same period is about 3 times higher in the inflow than the loch water. The concentration of this nutrient in the outflow is also higher than the loch water.

The changes in nutrient concentrations in the inflow are shown in Figure 2:5a and 2:5b. The soluble phosphate concentrations were relatively low in spring and summer, but the concentrations were moderately high in winter, whereas the total phosphate concentrations were generally high in

Table 2:3

The estimation of dominant phytoplankton species in Loch Kilconquhar, from 11/3/80 to 10/3/81.

Date	Species	cell (filament)/ml
11/3/80	Stephanodiscus sp	15,000
	Scenedesmus sp	500
2/4/80	Stephanodiscus sp	3,000
	Phytoconis sp	2,500
17/4/80	Stephanodiscus sp	5,000
	Actinastrum sp	300
1/5/80	Anabaena flos-aquae	30,000
	Scenedesmus sp	100
15/5/80	Anabaena flos-aquae	900,000
	Ankisdesmus sp	5,000
29/5/80	Anabaena flos-aquae	500,000
	Ankisdesmus sp	2,000
11/6/80	Ankisdesmus sp	2,500
	Scenedesmus sp	500
26/6/80	Aphanizomenon sp	7,000
	Ankisdesmus sp	1,000
9/7/80	Aphanizomenon sp	1,000
	Ankisdesmus sp	500
23/7/80	Synedra sp	500
	Scenedesmus sp	100
13/8/80	Aphanizomenon sp	30,000
	Gomphonema sp	1,000
26/8/80	Aphanizomenon sp	50,000
	Gomphonema sp	100
3/9/80	Aphanizomenon sp	150,000
	Gomphonema sp	200
13/10/80	Aphanizomenon sp	5,000
	Ankisdesmus sp	200
22/10/80	Gomphonema sp	500
	Navicula sp	100
5/11/80	Synedra sp	300
	Navicula sp	200
18/11/80	Synedra sp	250
	Scenedesmus sp	150
3/12/80	Scenedesmus sp	300
	Stephanodiscus sp	100
17/12/80	Stephanodiscus sp	1,500
	Scenedesmus sp	1,000
14/1/81	Stephanodiscus sp	20,000
	Navicula sp	500

Table 2:3 contd.

Date	Species	cell (filament)/ml
30/1/81	Stephanodiscus sp	30,000
	Navicula sp	1,500
18/2/81	Stephanodiscus sp	15,000
	Ankisdismis sp	3,000
11/3/81	Stephanodiscus sp	10,000
	Navicula sp	7,000

Table 2:4

Mean nutrient concentrations (mg l^{-}) ± 95% CL from the inflow, the loch and the outflow over a one year period, from 11 March 1980 to 10 March 1981.

	Sample (n)	SiO_2-Si	NO_3-N	PO_4-P
Inflow	22	2.01±0.46	5.23±0.38	0.020±0.004
Loch	23	1.62±0.05	1.52±0.05	0.140±0.008
Outflow	22	1.68±0.39	1.79±0.20	0.130±0.004

FIGURE 2:4

(opposite)

The mean concentrations of (PO_4-P) and (NO_3-N) from inflow, lake and outflow, over a period of one year from 11 March 1980 to 10 March 1981.

FIG. 2:4

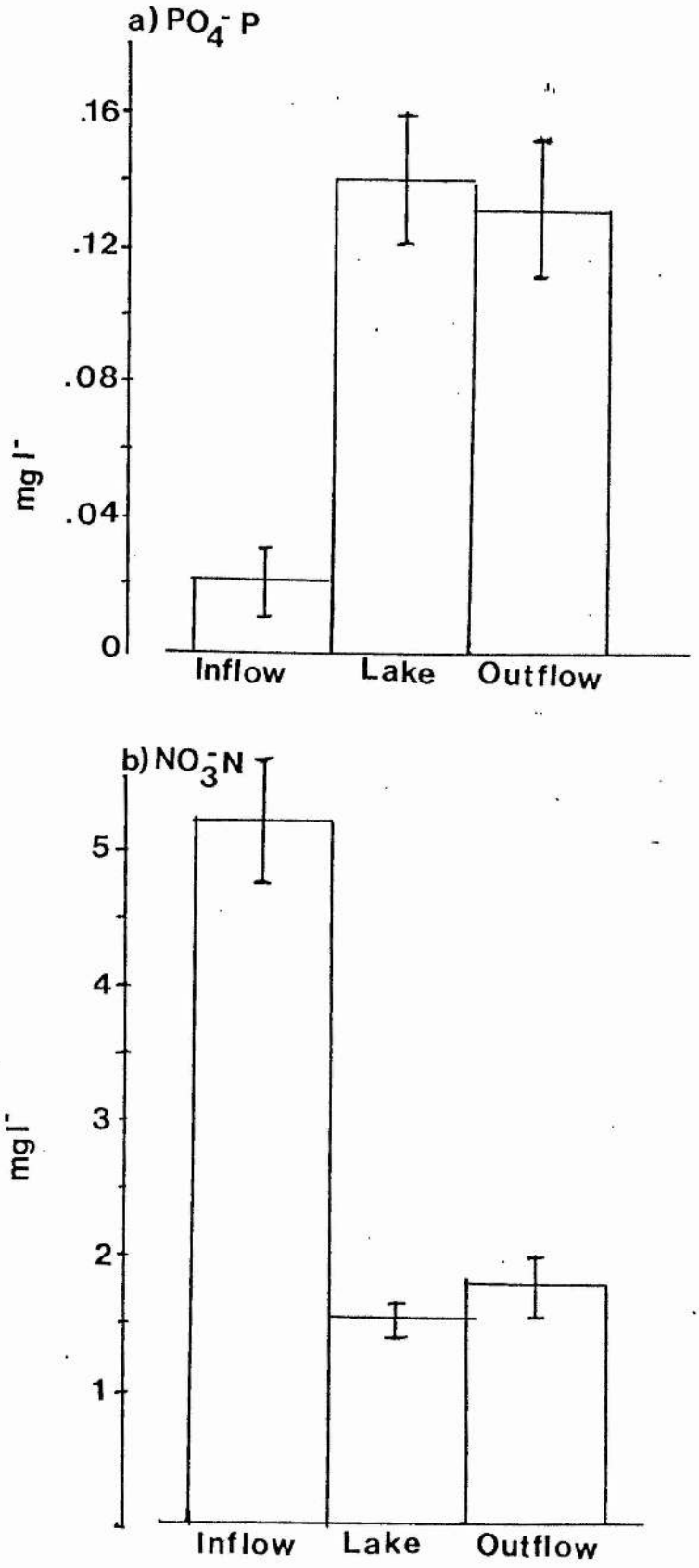

a) PO_4^- P
.16
.12
.08
.04
0
mg l⁻
Inflow
Lake
Outflow
b) NO_3^- N
5
4
3
2
1
mg l⁻
Inflow
Lake
Outflow

FIGURE 2:5

(opposite)

a) The total phosphate and the soluble reactive phosphate concentrations; b) the nitrate-nitrogen concentration of the inflow from 11 March 1980 to 10 March 1981.

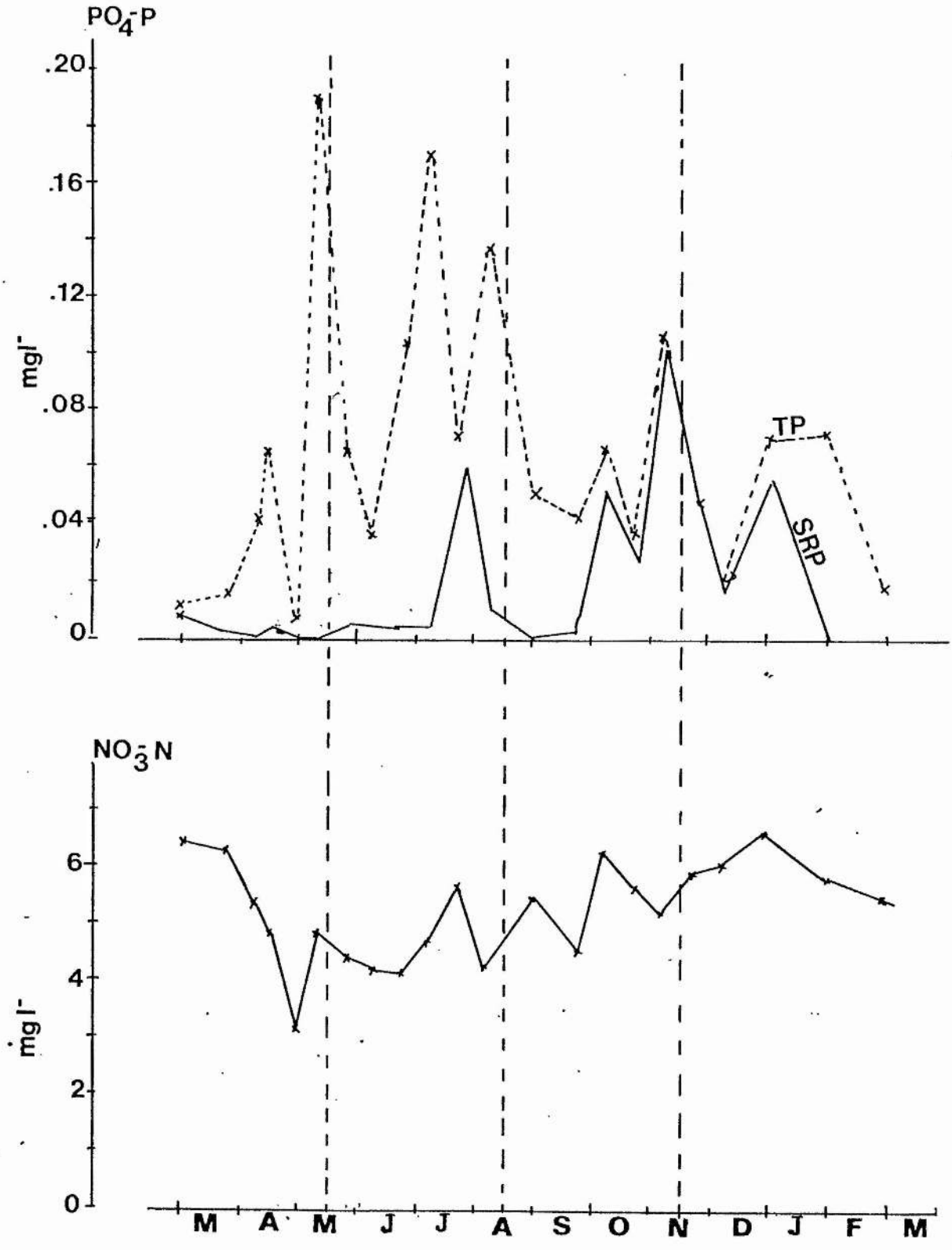


FIG. 2:5

summer but low in winter.

The soluble nitrate concentrations were extremely high in the inflow and reached a maximum of 6.65 mg/l $[NO_3-N]$ in January 1981. (Figure 2:5b). However, the concentrations were fairly low in summer and dropped to a minimum value of 3.10 mg/l $[NO_3-N]$ in the middle of May 1980.

Birds

From the estimation of bird population in Loch Kilconquhar, Table 2:5, it is apparent that the overall bird population was high in winter and this was mainly due to the large population of migratory duck. Common and herring gulls are found all the year round and coots are normally abundant in spring.

Laboratory experiments

Experiment 1:

One gram of fresh duck dropping has a mean content of 4170 ± 350 mg of total phosphate and 3610 ± 675 mg of total kjeldahl nitrogen. By contrast one gram of gull dropping has a mean content of 5072 ± 748 mg of total phosphate and 2634 ± 829 mg of total kjeldahl nitrogen (Table 2:6 and Figure 2:6).

Experiment 2:

In experiment 2, droppings were vigorously shaken in distilled water for 7 hours and sampled after 1 hour, then 2-hourly. Results for $[PO_4-P]$ are shown in Figure 2:7, while Table 2:7 also gives conductivity.

TABLE 2:5

Estimation of bird population in Loch Kilconquhar.

MONTH	1980 N	D	J	F	M	A	M	J	J	A	S	O	N	1981 D	J	F	M
Anatidae																	
Anser anser	++									+++					+		
Cygnus olar	+	+					+	++	++	++	++	+			+	+	+
Anas platyrhynchos	++	++	++	++	++	+	+	+	+	+	+++	+++	++	+++	+++	++	+
Anas acuta	+	+++	+++	+	+	+								+++	+++	++	++
Anas Clypeata		+++	+++											+++	+++		
Anas Ferina	+	++	++				++	++	+	+	+	+++					
Aythya Faligula	+	++	+							+	+	+++		+++	++	++	
Bucephala Clagula		+++	+												+++		
Rallidae																	
Fulica Atra	+	+++	+	++	+++	+++	+++	++	++	++	+	++	++	+	+	+++	+++
Gallinula Chloropus						+	+	+		+	+						+
Laridae																	
Larus canus	+++	++	++	+++	++	++	++	+	++	++	++	++	+++	+++	+++	++	++
Larus marinus	++	++	++											++	++		

+ = 1 10
++ = 10 100
+++ = 100

Table 2:6

The concentrations of total phosphate and total kjeldahl nitrogen from 1 g of fresh duck and gull dropping. Results are mean of five samples ± 95% CL (n = 5).

	Duck dropping		Gull dropping	
No.	Total Phosphate mg/kg fresh wt.	Kjeldahl Nitrogen mg/kg fresh wt.	Total Phosphate mg/kg fresh wt.	Kjeldahl Nitrogen mg/kg fresh wt.
1	3800	3040	4550	1750
2	3850	3300	5800	2100
3	4020	3010	5000	2050
4	4580	4800	4010	3770
5	4600	3900	6000	3500
	20850	22812	25360	13170
	4170 + 306	3610 + 591	5072 + 656	2634 + 727

FIGURE 2:6

(opposite)

The concentrations of total phosphate and total kjeldahl nitrogen from fresh duck and gull droppings. ((error bar) = 95% CL).

FIG. 2:6

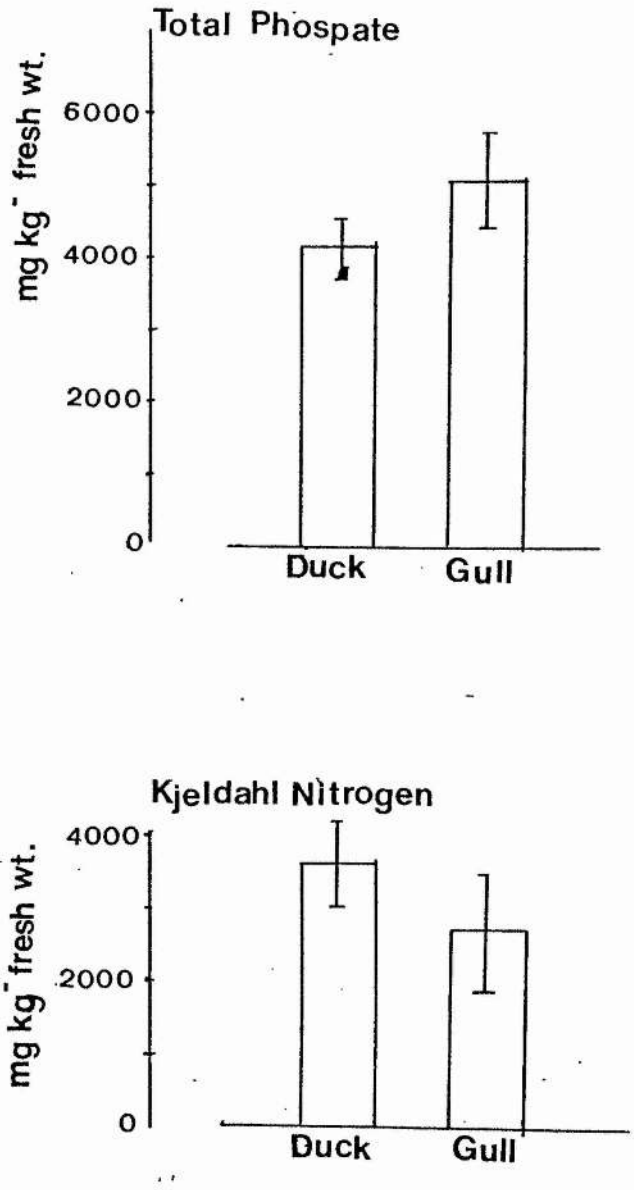

Total Phospate
mg kg⁻ fresh wt.
6000
4000
2000
0
Duck
Gull
Kjeldahl Nitrogen
mg kg⁻ fresh wt.
4000
2000
0
Duck
Gull

Table 2:7

The solubility of $[PO_4\text{-}P]$ in mg/l from 1 gm fresh duck and gull droppings after vigorously shaken in 250 ml of distilled water. Readings were taken every 2 hours (Mean: n = 4 ± 95% CL).

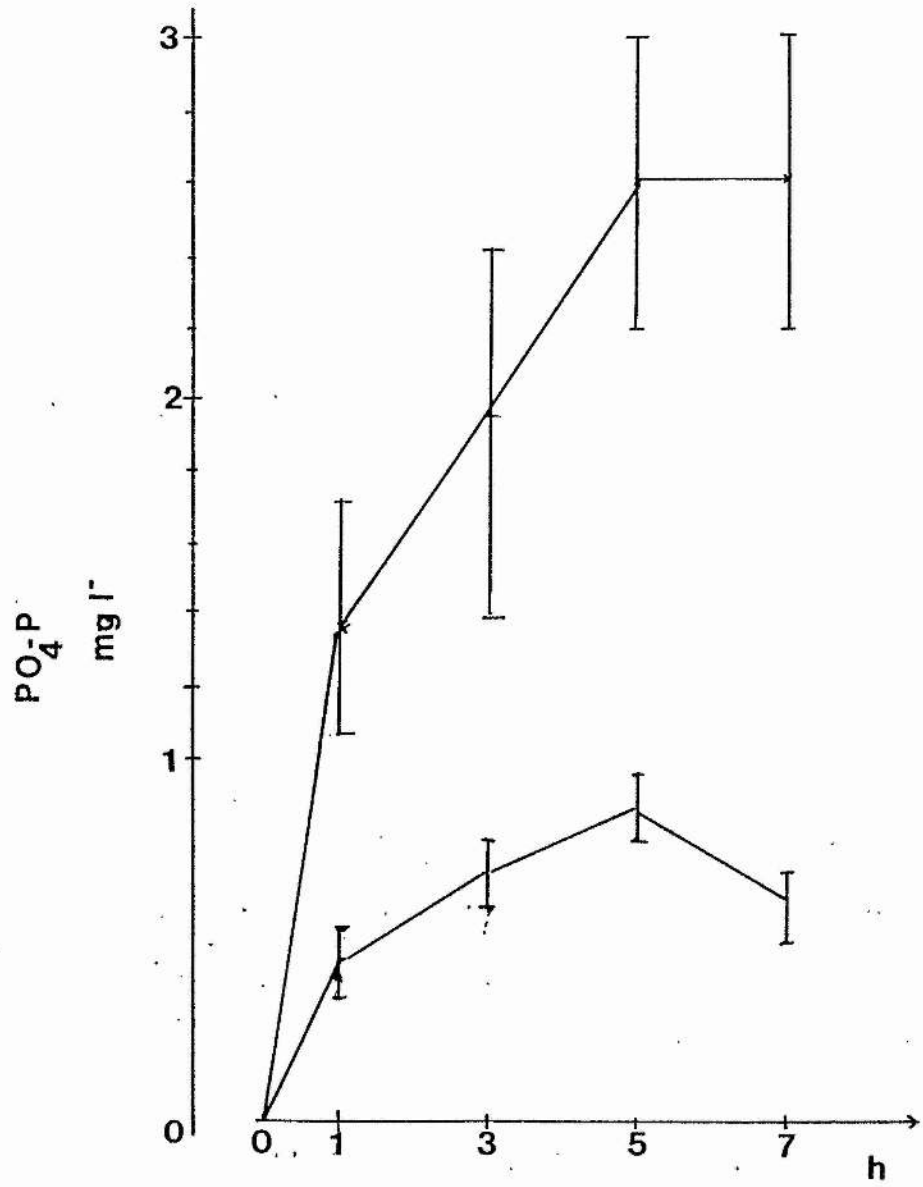
Time hrs.	Species	PO_4-P mg l^{-}	Conductivity umhos
1	duck	0.458 ± 0.018	
	gull	1.385 ± 0.485	
3	duck	0.593 ± 0.120	210 ± 9.8
	gull	1.875 ± 0.747	320 ±23.5
5	duck	0.870 ± 0.103	
	gull	2.620 ± 0.774	
7	duck	0.613 ± 0.050	
	gull	2.630 ± 0.671	

FIGURE 2:7

(opposite)

The solubility of 1 g of fresh gull and duck droppings in 250 ml of distilled water after vigorously shaken for 7 hours.

FIG. 2:7



Experiment 3:

Figure 2:8 and Table 2:8 present results of experiment 3; each compared the effect of sediment and duck dropping on $[PO_4\text{-}P]$, $[NO_3\text{-}N]$ and $[SiO_2\text{-}Si]$ of loch water. Over 4 days, lake sediment absorbed $[PO_4\text{-}P]$ but did not appear to affect $[NO_3\text{-}N]$ and $[SiO_2\text{-}Si]$. Over the same period, duck dropping increased concentration of all three nutrients, particularly $[PO_4\text{-}P]$.

Experiment 4a:

In experiment 4a decaying submerged macrophytes are also shown to release substantial amounts of soluble phosphate into the water (Figure 2:9). This figure shows that 1 gm of Cladophora produced more soluble phosphate than 1 gm of Myriophyllum and that after 5 weeks maximum release was observed from both these macrophytes at the controlled temperature of 15°C.

Experiment 4b:

The decaying of an Aphanizomenon bloom (210.85 chl a mg/m^3) increased the soluble phosphate and soluble nitrate concentrations by two and three times respectively in 2 weeks; the conductivity increased slightly (Table 2:9). However, there is a drop in dissolved oxygen concentration and pH value in the unstirred flask.

FIGURE 2:8

(opposite)

The effect of loch sediment and duck dropping on Loch Kilconquhar water (29 January 1980) at 5°C.

FIG. 2:8

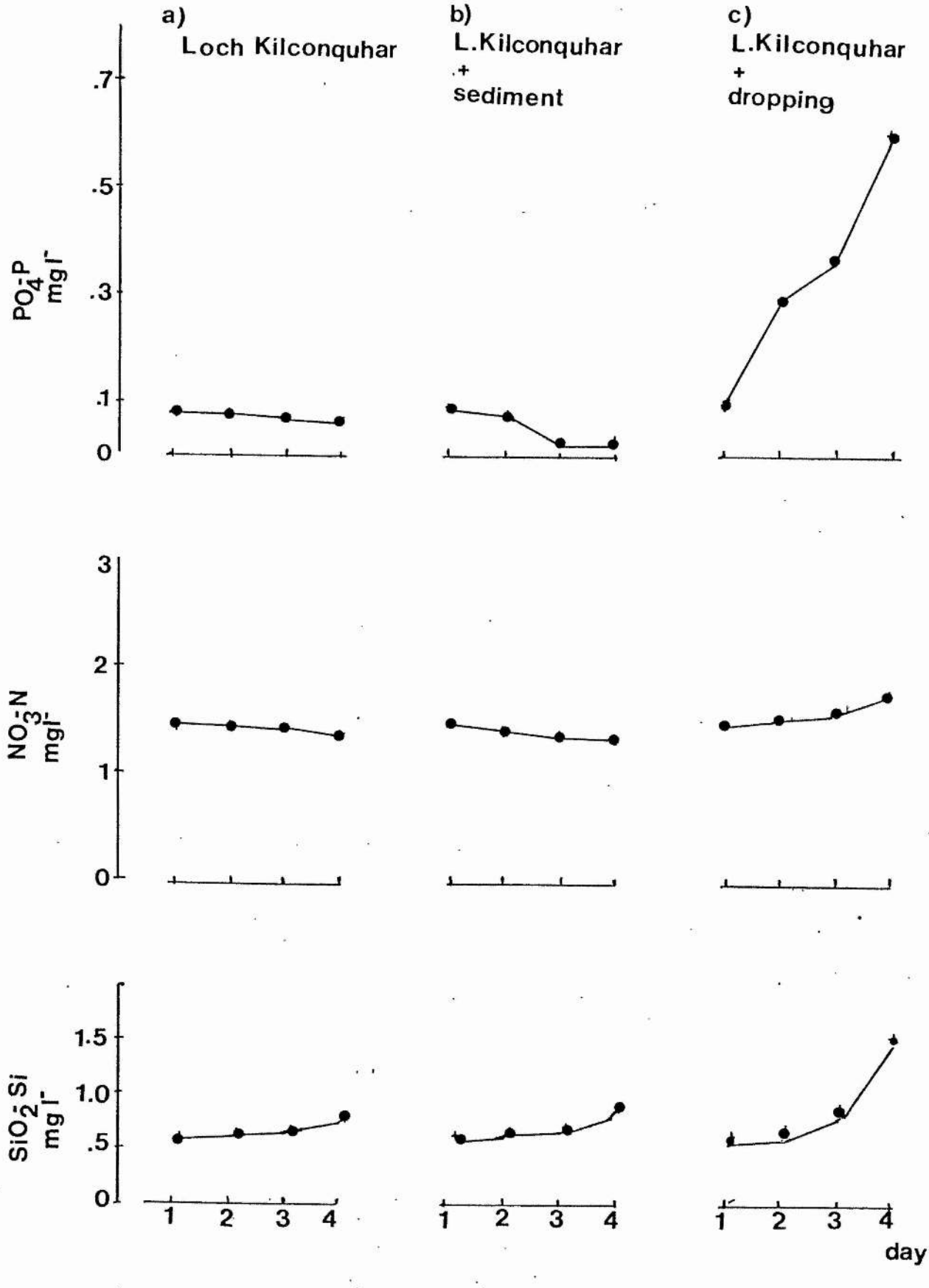

a)
Loch Kilconquhar
b)
L.Kilconquhar
+
sediment
c)
L.Kilconquhar
+
dropping
PO_4-P mgl⁻
.7
.5
.3
.1
0
NO_3-N mgl⁻
3
2
1
0
SiO_2-Si mgl⁻
1.5
1.0
.5
0
1 2 3 4
day

Table 2:8

The effect of loch sediment and duck dropping on Loch Kilconquhar water; a) Loch Kilconquhar water sample dated 29/1/80, b) one gram of fresh Loch Kilconquhar sediment was added to 50 ml Loch Kilconquhar water 29/1/80 and c) one gram of fresh duck dropping was added to 50 ml of Loch Kilconquhar water (29/1/80). (Mean; n = 3 ± 95% CL).

Date	Sample	(PO_4P) mg l^{-}	(NO_3-N) mg l^{-}	(SiO_2-Si) mg l^{-}
29/1/80	a	0.088±0.001	1.450±0.011	0.580±0.023
	b	0.088±0.001	1.450±0.011	0.580±0.023
	c	0.088±0.001	1.450±0.011	0.580±0.023
30/1/80	a	0.087±0.001	1.440±0.033	0.600±0.045
	b	0.070±0.003	1.400±0.057	0.610±0.067
	c	0.290±0.090	1.500±0.080	0.613±0.113
31/1/80	a	0.070±0.002	1.420±0.036	0.640±0.226
	b	0.020±0.005	1.360±0.054	0.700±0.113
	c	0.360±0.023	1.520±0.136	0.800±0.113
1/2/80	a	0.069±0.002	1.300±0.051	0.760±0.226
	b	0.031±0.008	1.310±0.113	0.880±0.113
	c	0.600±0.011	1.700±0.272	1.500±0.113

FIGURE 2:9

(opposite)

The release of $[PO_4\text{-}P]$ mg l^{-} from 1 gm of Cladophora fracta (n = 4) and Myriophyllum spicatum (n = 4). Each plant was placed in 100 ml of distilled water in a flask completely covered with aluminium foil to prevent photosynthesis at 15°C.

FIG : 2:9

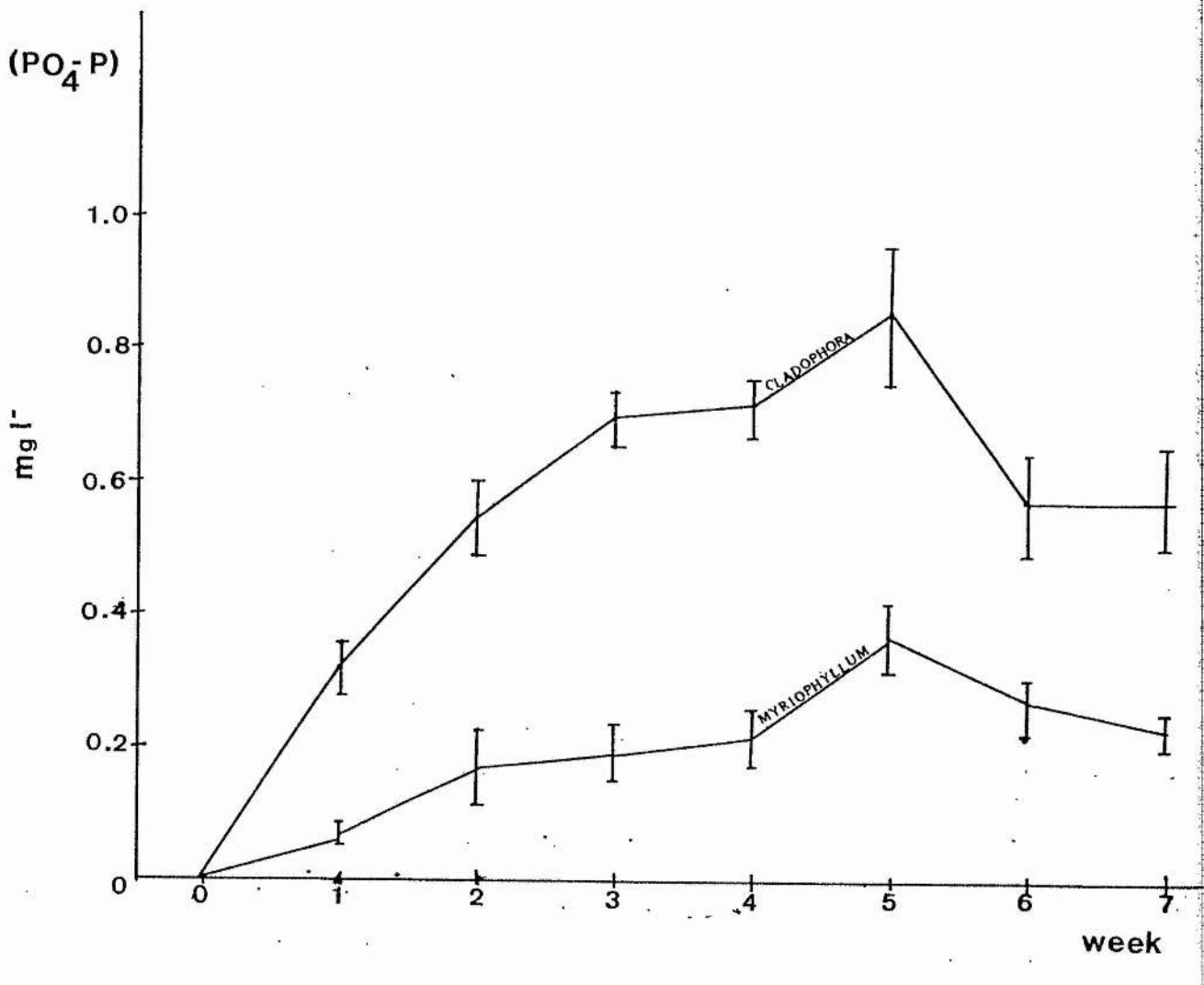

(PO4- P)
mg l-
1.0
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
week
CLADOPHORA
MYRIOPHYLLUM

Table 2:9

Changes of nutrient concentrations and various other properties of a water sample containing an Aphanizomenon bloom after incubation for 14 days in the dark at 15°C.

	Date 26 June 1980	Date 8 July 1980		% increase
$[PO_4\text{-}P]$ mg l^{-}	0.68	1.33	+0.65	+96%
$[NO_3\text{-}N]$ mg l^{-}	1.80	5.55	+3.75	+208%
DO cons. mg l^{-}	3.60	1.50	-2.1	-58%
pH	7.75	7.43	-0.32	-4%
Conductivity umhos	520	560	+40	+8%

2.3) DISCUSSION

The high concentrations of soluble phosphate (SRP; PO_4-P) and soluble nitrate (NO_3-N) indicate that Loch Kilconquhar is a nutrient-rich freshwater loch. It is interesting to note that the phosphate concentration in this loch is exceptionally high compared with other freshwater lochs in Scotland (Table 2:10).

There are several possible sources of this high concentration of which the most likely are bird droppings and to a lesser extent drainage from the arable land.

Burton (1977), Leah et al. (1978), Edington (1977), Nilsson (1978) and Pelikan et al. (1978) have indicated that birds, particularly wildfowl and gulls, can play a significant role in bringing nutrients into freshwater lakes. The fact is that their droppings have a fertilizing effect and, according to Leentvaar (1966), ducks, geese and other waterfowl are normally reared on Polish fish ponds in order to get a sufficient supply of phosphate in the water. As a result the ponds, crowded with ducks or geese, are occasionally green in colour due to dense algal growth.

As stated previously, Loch Kilconquhar is noted for its bird population and a well-known bird watcher, Goodners (1974) considered Loch Kilconquhar as a particularly good lake for observing a wide variety of duck species, especially in winter. Pelikan et al. (1978) further added that lakes in waterfowl reserves and sanctuaries are normally in a state of eutrophication through the effect of wildfowl excrements.

Table 2:10

The mean soluble phosphate (PO_4-P) concentrations from Scottish lochs.

No.	Loch	Mean $[PO_4\text{-}P]$ mg/l	Reference
1)	Upland Scottish lochs	≃ 0.006 Total phosphate. (Soluble phosphate is beyond the limit of detection.)	Moss (1981)
2)	Loch Lomond (Balmaha Station)	0.006	Maulood and Boney (1980)
3)	Loch Etive (sea loch)	0.007	Solorzano (1978)
4)	Loch Creran (sea loch)	0.015	Solorzano (1978)
5)	Loch Leven	0.021	Holden and Caines (1974)
6)	Loch Lindores	0.016	1981 (this thesis)
7)	Loch Kilconquhar	0.141	1981 (this thesis)

As indicated by Nilsson (1978) most of the eutrophicated lakes in Southern Sweden have more bird species than oligotrophic lakes from the same area. He also concluded that there is a positive correlation between bird community density and total phosphate concentration in the water. It is not surprising therefore that Loch Kilconquhar shows signs of eutrophication.

Although natural eutrophication is normally a slow process compared with cultural eutrophication, when a large quantity of droppings are deposited in a relatively small lake, the rate of eutrophication is bound to be speeded up and can apparently, compare closely to rates of cultural eutrophication.

The ducks are the most characteristic of freshwater birds. Gardarsson (1979) observed that Cladophora seemed to be the major diet of ducks in Lake Myvatn, Iceland, and it seemed the duck family is normally attracted to the lake which offers varieties of "soft, tender water plants". Due to the highly vegetative diet, their droppings are "grassy". It is interesting to note that Proctor (1962) observed that Chara and Nitella survived a normal passage through the digestive tract of migratory ducks and suggested that many plants are dispersed in this manner. So it is of interest to note that in the present study, it was observed that Cladophora and Zannichellia grew from duck droppings collected in Loch Kilconquhar, which were left unattended for several weeks in test tubes filled with water.

Gulls are generally associated with the coast, but they are also characteristic of freshwater habitats near the coast.

Unlike ducks, they normally come to a loch to roost and at the same time may provide substantial amounts of nutrients to the loch ecosystem through their faeces. According to Vernon (1972) common gulls are omnivorous, their food varying from marine molluscs, fish scraps and earthworms to vegetable remains on rubbish tips and cereal grain. From the present results, gull droppings contain more phosphate than the ducks' and are also more soluble in water.

Leah et al. (1978) whose work deals mainly with the effects of black headed gulls on Hickling Broad, Norfolk, clearly indicated that droppings of this gull contain readily soluble combined phosphate and nitrate. In both cases, much of the soluble phosphate and nitrate is likely to be rapidly leached out into the lake water before the dropping reaches the sediment.

The accumulation of bird droppings, substantial amounts of decaying algal blooms and dead plant material may lead to oxygen deficits developing at surface of loch sediments in summer. This too will facilitate nutrient release (Mortimer, 1971). Admittedly, the subject of phosphate release from sediment is related, among other factors, to oxygen concentration at the sediment and to the total phosphate concentration in the sediment. This is dealt with under field and laboratory conditions in the next chapter. Here it is noted that a correlation existed ($r = -0.72$) between soluble phosphate (SRP = soluble reactive phosphate) and dissolved oxygen concentration in the loch during summer 1980 (Figure 2:10) and between SRP and total phosphate (TP) in the sediment (Figure 2:11). These data suggest that there was release

FIGURE 2:10

(opposite)

Correlations between soluble phosphate and dissolved oxygen concentrations at Station A in Loch Kilconquhar in summer, 15 May 1980 to 23 July 1980. The straight line represents regression equation ($y = 0.062\ x + 0.976$; $r = -0.724$).

Fig. 2.10

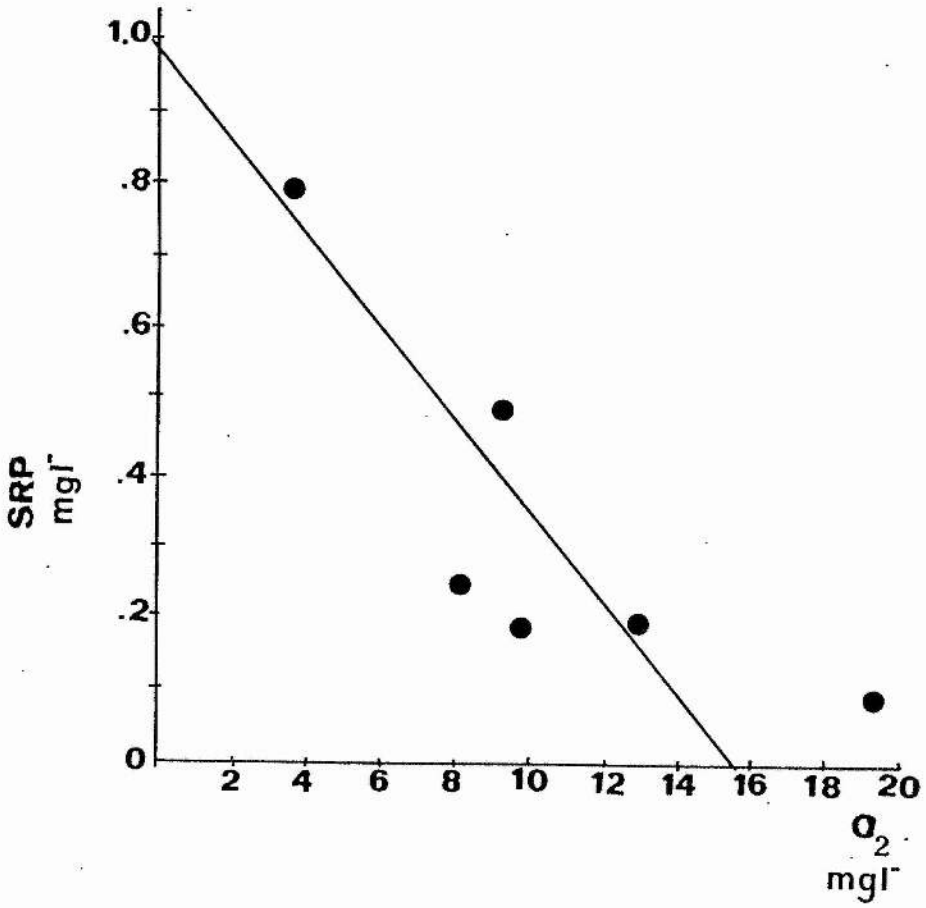


FIGURE 2:11

(opposite)

Correlations between integrated soluble phosphate from the water and total phosphate from the loch sediment in the year 1980. The straight line represents regression equation
($y = 0.0021\ x + 0.4424$; $r = 0.708$).

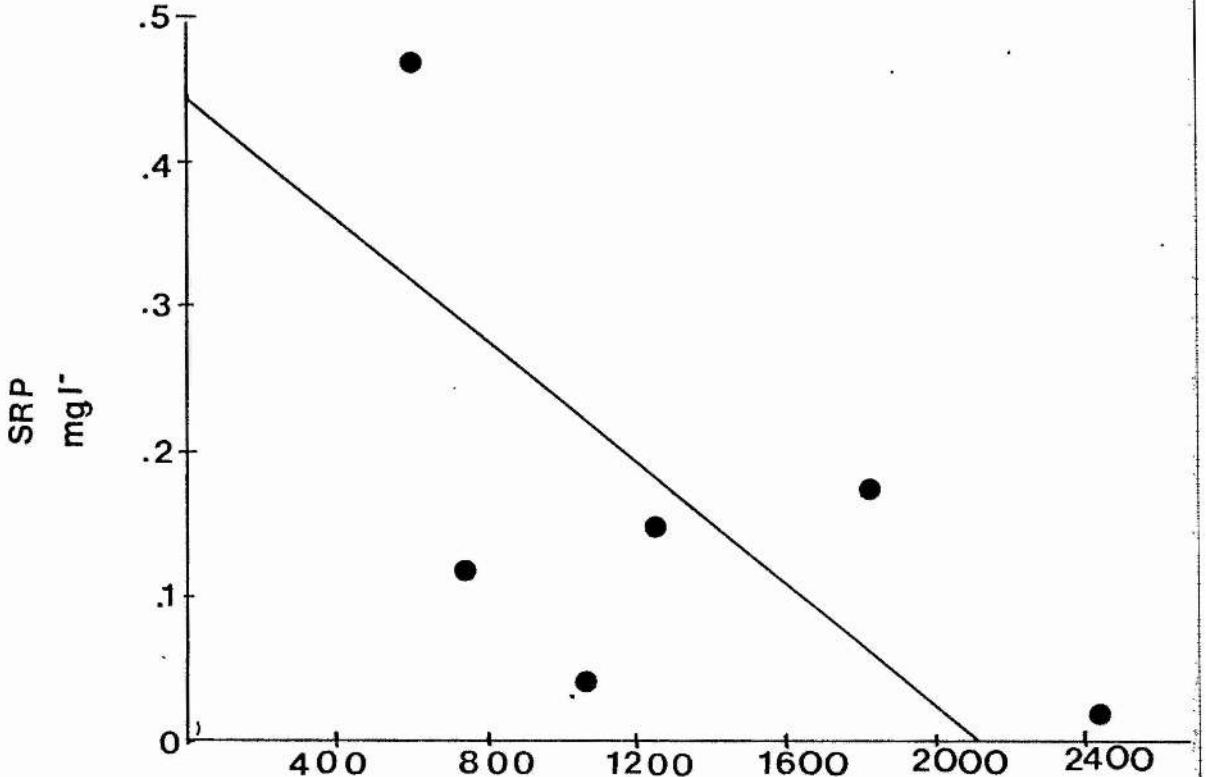


FIG. 2:11

of phosphate from the sediment and this could possibly explain the high soluble phosphate in the loch water compared with that in the inflow.

Moreover, it is a well-known fact that decaying phytoplankton and macrophytes could also result in increasing of nutrients in the loch water (Richey 1979, Bloesch et al. 1977, and Welch et al. 1979). Apart from decaying, Barko and Smart (1980) and Carpenter (1980) observed that submerged macrophytes could help in releasing phosphate from the sediment into the water column either by leaching or excretion of nutrients from shoots of plants whose roots penetrate the sediments. That is, the normal mud surface barrier to nutrient release to overlying water is by-passed (Spence 1981).

Holden and Caines (1974) stated that the major source of nitrate in Loch Leven is undoubtedly the large quantity of nitrogenous fertilizers leached out from the agricultural land in the catchment area. Presumably the same phenomenon occurs in Loch Kilconquhar and according to Cooke and Williams (1974) most agricultural drainage in Britain contains a high concentration of soluble nitrate. Table 2:11 further indicates that drainage from agricultural areas is generally high in nitrate compared with phosphate.

Obviously such a high concentration of nitrate in the drainage inflow will increase the nutrient concentration in Loch Kilconquhar and indirectly affect the loch ecosystem as a whole. Although the phosphate concentration in the inflow is low, it could result in accumulation of phosphate in the long term and therefore play a significant role in bringing this nutrient to the loch.

Table 2:11

The mean soluble nitrate and total phosphate concentrations from land drains (inflow).

No.	Land drain from	NO_3-N mg/l	Total Phosphate mg/l	Reference
1)	Intensively-farmed area of sandy soils (at Woburn)	22.5	0.08	Cooke and Williams (1970)
2)	Area of high and rough neglected grassland (at Woburn)	3.3	0.08	Cooke and Williams (1970)
3)	Drain feeding a cattle trough (at Woburn)	8.1	0.24	Cooke and Williams (1970)
4)	Spring (at Woburn)	11.0	0.14	Cooke and Williams (1970)
5)	Lake (at Woburn)	1.9	0.02	Cooke and Williams (1970)
6)	Area of arable land (inflow: Kilconquhar)	5.5	0.02	1981 (this study)
7)	Lake (outflow: Kilconquhar)	1.75	0.13	1981 (this study)

2.4) CONCLUSION

The dense bird population strongly, and agricultural run-off to a lesser extent, affect the nutrient composition of Loch Kilconquhar water. Related to this, the annual release of nutrients, particularly phosphate, from sediment makes Loch Kilconquhar one of the few Scottish loch waters in which that nutrient reaches very high concentrations.

The results show that bird droppings are rich in nutrients, particularly phosphate and nitrate. The major source of phosphate in the loch is undoubtedly the bird droppings. In addition to its presence in bird droppings, drainage from arable land is also high in nitrate. So a major source of nitrate is nitrogenous fertilizer.

From experiments conducted in the laboratory, it is concluded that decaying submerged macrophytes and algal blooms can increase substantially the amounts of soluble phosphate in lake water. In addition to bird droppings, a decaying algal bloom is also mainly sedimented on to the lake bottom. These organic supplies may in turn deplete the dissolved oxygen concentration at sediment-water interface and result in nutrient release. Thus, in Loch Kilconquhar, on each of two occasions during the studied period, nutrient release from loch sediment occurred after the collapse of algal blooms, the soluble phosphate concentration in the water increased and the dissolved oxygen in the water diminished.

Laboratory studies also showed that Loch Kilconquhar sediment is able to absorb and retain soluble phosphate from the loch water. This clearly indicated that soluble phosphate

can be incorporated in the loch sediment and it seemed that a pool of phosphate is stored in the loch sediment by this mechanism.

CHAPTER 3

NUTRIENT RELEASE FROM LOCH KILCONQUHAR SEDIMENT

3 . 1) AIMS AND METHODS

Evidence in a previous chapter strongly suggests that there was a substantial release of nutrients from Loch Kilconquhar sediment into the water in warm conditions. (Refer to Chapter 2, Figure 2:10 and Figure 2:11.)

It is fairly important to know the underlying causes of the nutrient release. It was, therefore, hypothesised that the observed falls in dissolved oxygen content would relate to falls in redox potential which in turn could result in this nutrient release. Series of experiments were carried out in the laboratory on this aspect.

Apart from this, several additional samplings were done in the loch at night and early in the morning, during summer 1980.

1) Field sampling

1.1 Dissolved Oxygen concentration at Station A

In order to have some idea of the changes in dissolved oxygen (DO) concentration in the loch, particularly at night, as stated above several additional field samplings were done at 6 p.m. (1800 hours), 12 mid-night (2400 hours) and 6 a.m. (0600 hours).

The samples were all taken from surface water at Station A. For DO concentration, they were collected in 250 stoppered bottles to which 0.5 ml of manganese sulphate and 0.5 ml of Winkler's reagent were immediately added after collection of the samples.

Subsequently they were analysed in the laboratory for

DO concentrations by following the rest of the Winkler method. The full details of this particular method have been described in Chapter 1.

1.2 Soluble phosphate and pH

In this context, the drop in DO concentration is presumed, as is frequently the case, to be associated with the release of soluble phosphate from the loch sediment into the water. To prove that the release generally occurs when the DO concentration is low (particularly at night) the filtered water samples were also analysed for soluble phosphate. The analysis was done immediately after the water was transported to the laboratory. At the same time pH of the water samples was measured.

1.3 Hourly changes in DO concentration

The hourly changes in DO concentration were further monitored on several occasions in the loch itself. The 395530 oxygen sensor (oxygen electrode) was securely tied to a one-meter pole, about 0.25 m below the water surface.

The sensor was connected to the oxygen meter (Beckman field lab. oxygen analyzer) by a two-meter wire. The chart recorded was powered by a battery which was also connected to the oxygen meter (Figure 3.1).

The oxygen meter, the chart recorder and thebattery were sheltered in the boat house and the door was locked to avoid any unwanted disturbance, particularly at night while the apparatus was left running over a period of 18 hours.

FIGURE 3:1

(opposite)

The set up for measuring changes in DO concentrations by oxygen meter over 18 h periods.

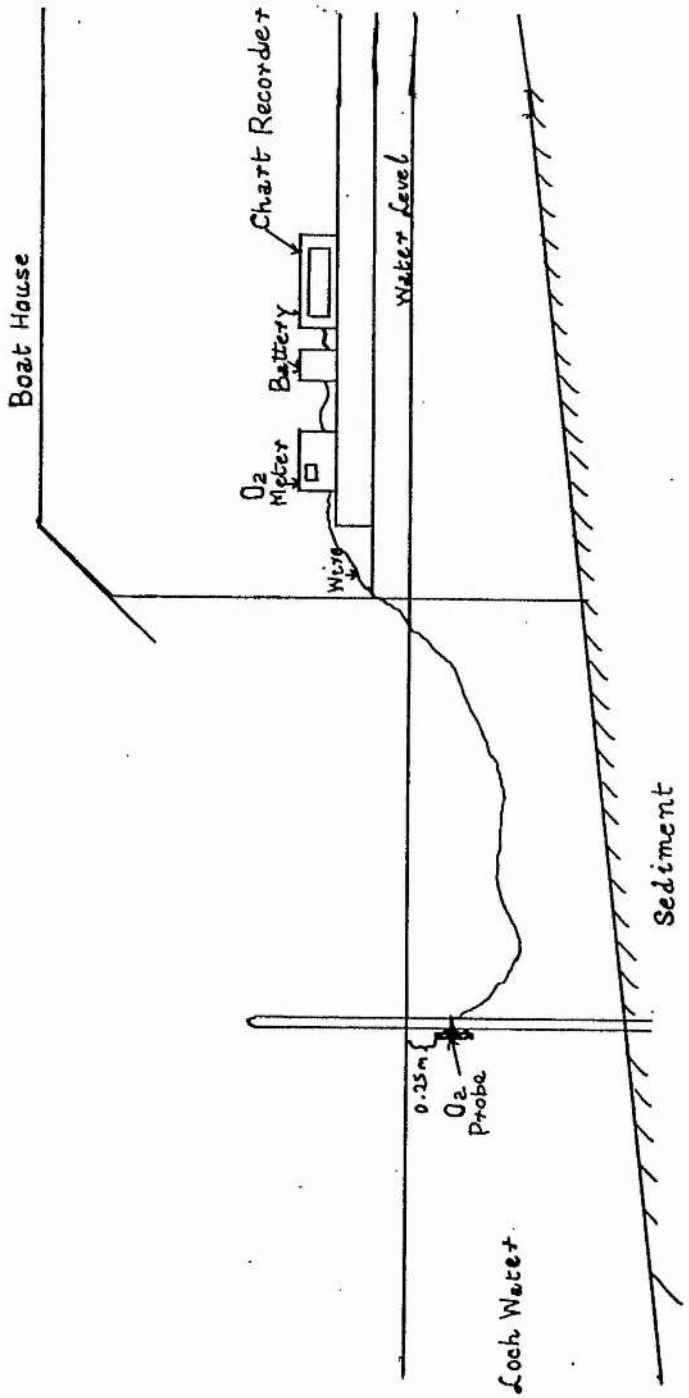

Boat House
Chart Recorder
Battery
O_2 Meter
Wire
Water Level
Sediment
0.25m
O_2 Probe
Loch Water

FIG. 3:1

2) Laboratory experiments

2.1 Redox potential

Generally overall biological activity particularly of micro-organisms can be followed by the measurement of oxidation-reduction potentials.

Micro-organisms metabolize by transferring electrons in chemical reactions from one compound to another and so increase the proportion of ions in the reduced state relative to those in the oxidized state. The rate of formation of reduced materials is an indication of the rate of microbial activity.

If a reference electrode and an inert measuring electrode are inserted in a solution containing both oxidized and reduced ions, a potential is produced between the electrodes, the sign and magnitude of which depend upon the type and concentrations of ions in each state.

In a complex system such as was studied for this thesis, there are many chemical ions involved, so only the overall changes in the oxidation-reduction state can be measured.

Redox potential was determined at a bright platinum electrode, connected to a saturated calomel electrode by a D.C. Microvoltmeter type TM 10 (Figure 3:2). Various platinum electrodes were used in this experiment in order to get a precise potential reading at known distances above or below the mud-water interface (Figure 3:3).

At the same time, pH values of the samples were determined to provide a standard for the comparison of different samples. Here the standard or reference value is at pH 7, termed E_7, and the potential measured is increased by 58 mVolt, for every one unit of pH above 7 or correspondingly reduced for

FIGURE 3:2

(opposite)

Redox potentials are taken by a series of platinum electrodes at various depths above and below the sediment-water interface.

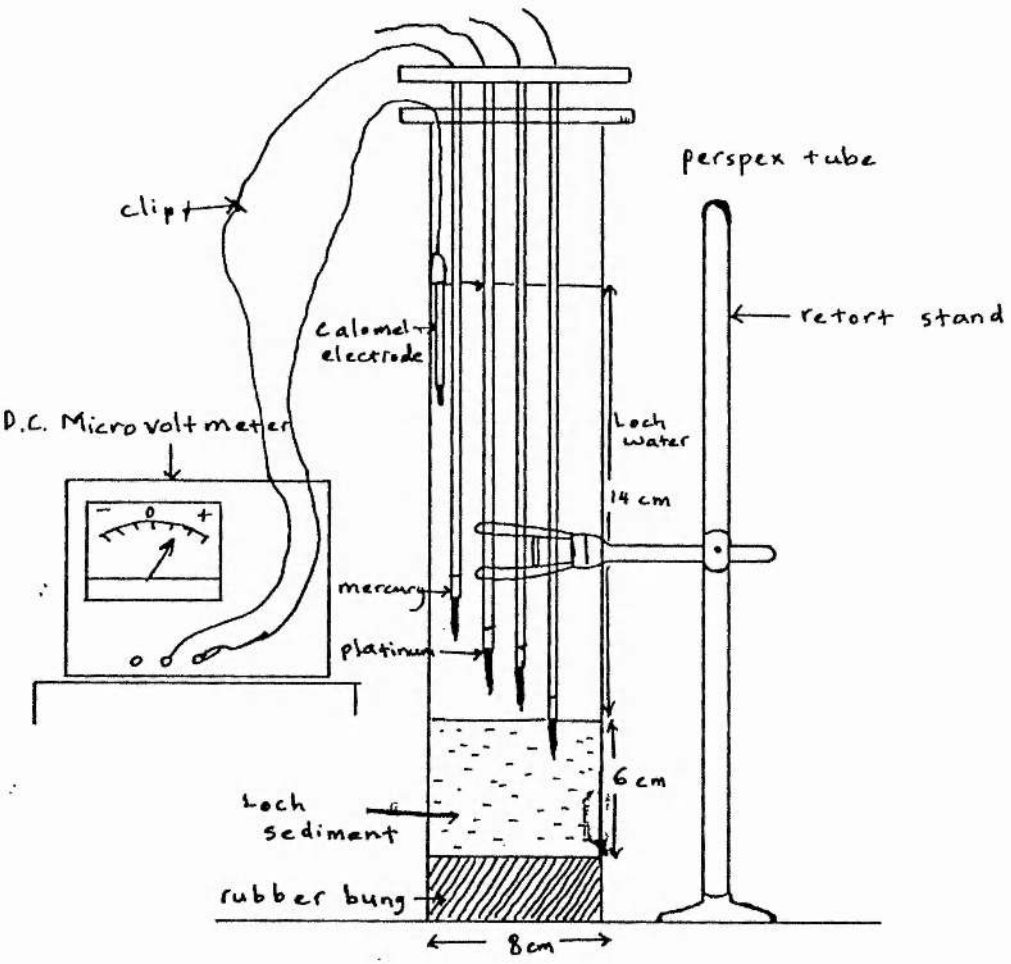

perspex tube
clip
retort stand
calomel electrode
D.C. Microvoltmeter
Loch water
14 cm
mercury
platinum
6 cm
Loch sediment
rubber bung
8cm

FIG. 3:2

FIGURE 3:3

(opposite)

a) A home made platinum electrode (made by a former research student (A. Dale)); it was rejuvenated for this experiment.

b) Platinum electrode Type P+ 805 ingold (Swiss made).

PLATINUM ELECTRODE

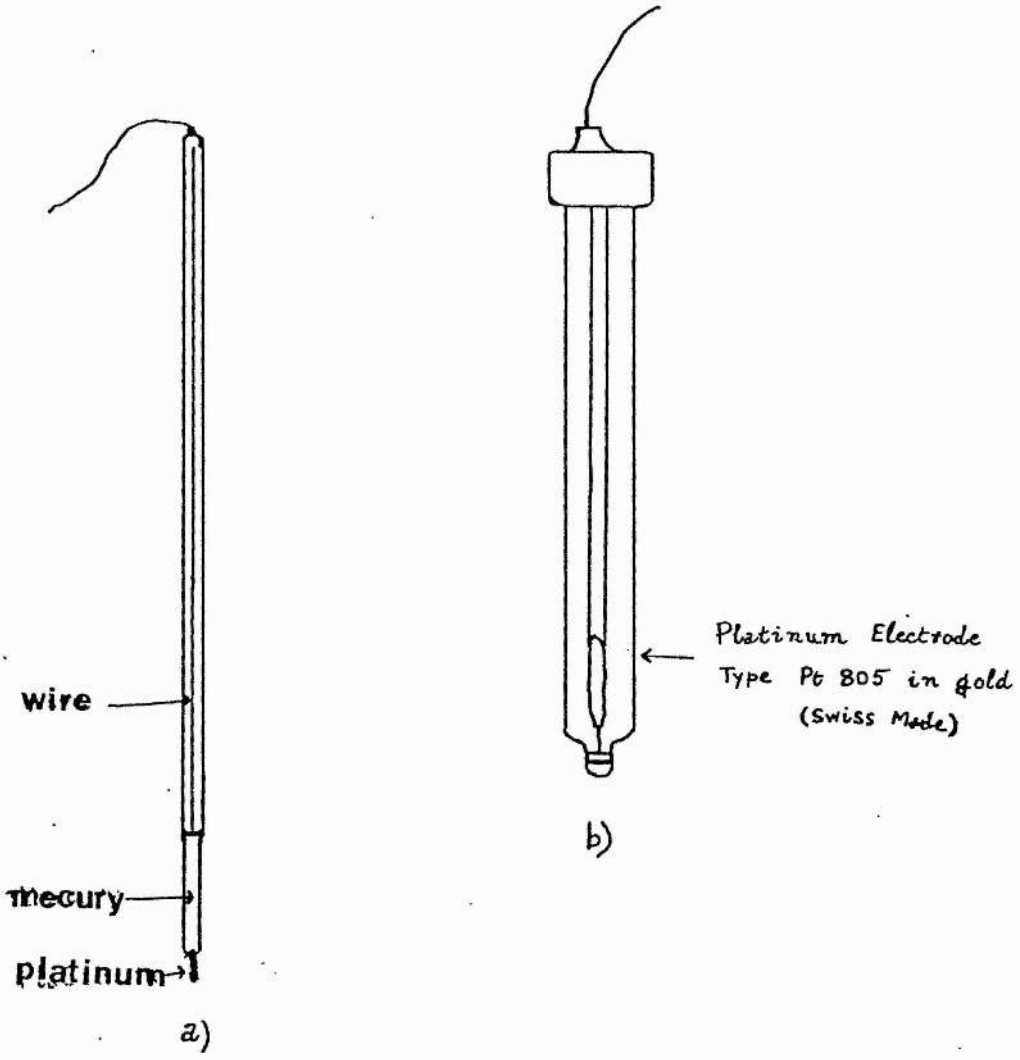


FIG. 3:3

pH value below 7.

Since the calomel electrode differs from the standard hydrogen electrode, 250mVolt is added to the measured reading regardless of the sign.

This method is a modification of conventional methods used by Pearsall and Mortimer (1939), Mortimer (1941), Mortimer (1971) and Viner (1974).

2.2 Ammonium-nitrogen (NH_4-N)

Since ammonia is found in a considerable quantity in the reduced state and furthermore, biological wastes such as excreta are closely associated with ammonia, on several occasions the ammonium concentration of samples was also determined, by the method of Solorzano (1964).

The following reagents were freshly prepared:

1) Phenol-alcohol solution:-

   10 g of phenol was dissolved in 100 ml 95% v/v ethyl alcohol.

2) Sodium nitroprusside 0.5%:-

   One g of sodium nitroprusside was dissolved in 200 ml water.

3) Alkaline solution:-

   100 g of trisodium citrate were dissolved in 5 g of sodium hydroxide in 500 ml water.

4) Oxidizing solution:-

   100 ml sodium nitrate solution were mixed with 25 ml hypochloride.

The procedure consists of successive additions of 1 ml phenol solution and 1 ml oxidizing reagent to 25 ml sample

in a 25 ml volumetric flask, mixing thoroughly after each addition. The colour is allowed to develop at room temperature for 1 h and the absorbance is recorded at 640 nm in a spectrophotometer. A standard curve was drawn in order to obtain the ammonia concentration for the sample against blank prepared by using distilled water in place of the sample.

2.3 Oxygen produced by submerged macrophytes and algal blooms. (The overall method was principally based on Vollenweider (1974).)

The changes in DO concentration in the loch is mainly due to the activity of living organisms. During the day, the water plants and phytoplankton help to increase the DO concentration in the loch water by photosynthesis.

Three species of submerged macrophytes freshly collected from the loch were used to observe the amount of oxygen produced by these plants in 24 hours at a constant water temperature of 15°C. They were the same plants which were used for other experiments, namely Myriophyllum spicatum, Cladophora fracta and Zannichelia palustris.

One gram of fresh Myriophyllum spicatum, Cladophora fracta and Zannichelia palustris was each placed in a separate 250 ml stoppered bottle (the same type of bottle was used for field oxygen analysis). The plants in these bottles were allowed to photosynthesize for 18 h under natural light.

In addition, three 250 ml stoppered bottles were fully covered with aluminium foils, to each of which had previously been added one gram of fresh shoots of each of these species.

Results gave a measure of dark respiration.

All these bottles had previously been filled with tap water and plants, after being covered with foils, were placed in a water bath at a constant temperature of 15°C for 24 hours. The initial DO concentration was measured on the tap water used in the experiment but without plants.

The same method was used for phytoplankton. The only difference was that, instead of tap water, natural loch water containing the phytoplankton was used.

The first sample was taken during the Stephanodiscus bloom in winter 1979-80. The experiments were run at a constant water temperature (15°C) and a daylength at this time of the year of 6 hours.

The second sample was taken during the Anabaena bloom in early summer when daylength was 18 hours.

Three 250 ml Pyrex bottles were used for each of these experiments. One of the bottles was directly used to measure the initial DO concentration from the loch water. The remaining pair were placed in the water bath at a controlled temperature of 15°C, one being covered with aluminium foil to prevent photosynthesis, the other being exposed to the natural light.

2.4 Experiments with two-meter perspex tube (nutrient release)

A two-meter perspex tube with a diameter of 8 cm was used to take a 1.5 m column of loch water along with 0.2 m depth of sediment. Two people are needed to handle the heavy tube, particularly when it is filled with the loch water and its sediment.

The initial sampling was done in the loch itself, at Station B on 6 Nov. 1979. First, the DO concentrations were measured at various depths and at the same time water samples were collected from the same depths for nutrient analysis.

Secondly, the long tube was slowly lowered into the loch water and allowed to penetrate the sediment. When the tube was filled, it was carefully pulled up. Before the whole tube came out of the water at precisely 0.20 m below the water surface, the lower end was plugged with a rubber bung.

The upper end was also plugged with a rubber bung, then the tube was safely placed on the dinghy. (By doing this it would also help to create an anoxic condition in the tube at a much faster rate (Figure 3:4).)

Special attention and care were taken during the transportation of this tube from the loch to the laboratory, to avoid tilting or undue disturbance. The tube was then placed in a special box in the laboratory so that it would stand in the upright position and left for 80 days before the final sampling on the loch water from the tube was done on 25 Jan. 1980.

2.5 Experiments with 0.75 m perspex tubes (nutrient release)

Two 0.75 m perspex tubes (diameter 8 cm) were used to sample loch water and a sediment core at Station A, in a shallow part of the loch with a water depth around 0.5 m.

The initial sample was taken on 25 March 1981. Chemical analyses were carried out or completed in the laboratory where redox potential was also measured.

FIGURE 3:4

(opposite)

a) shows how the sampling was done by using a 2 m-long perspex tube at Station B in Loch Kilconquhar and b) shows the tube was left in an upright position for 80 days in the laboratory.

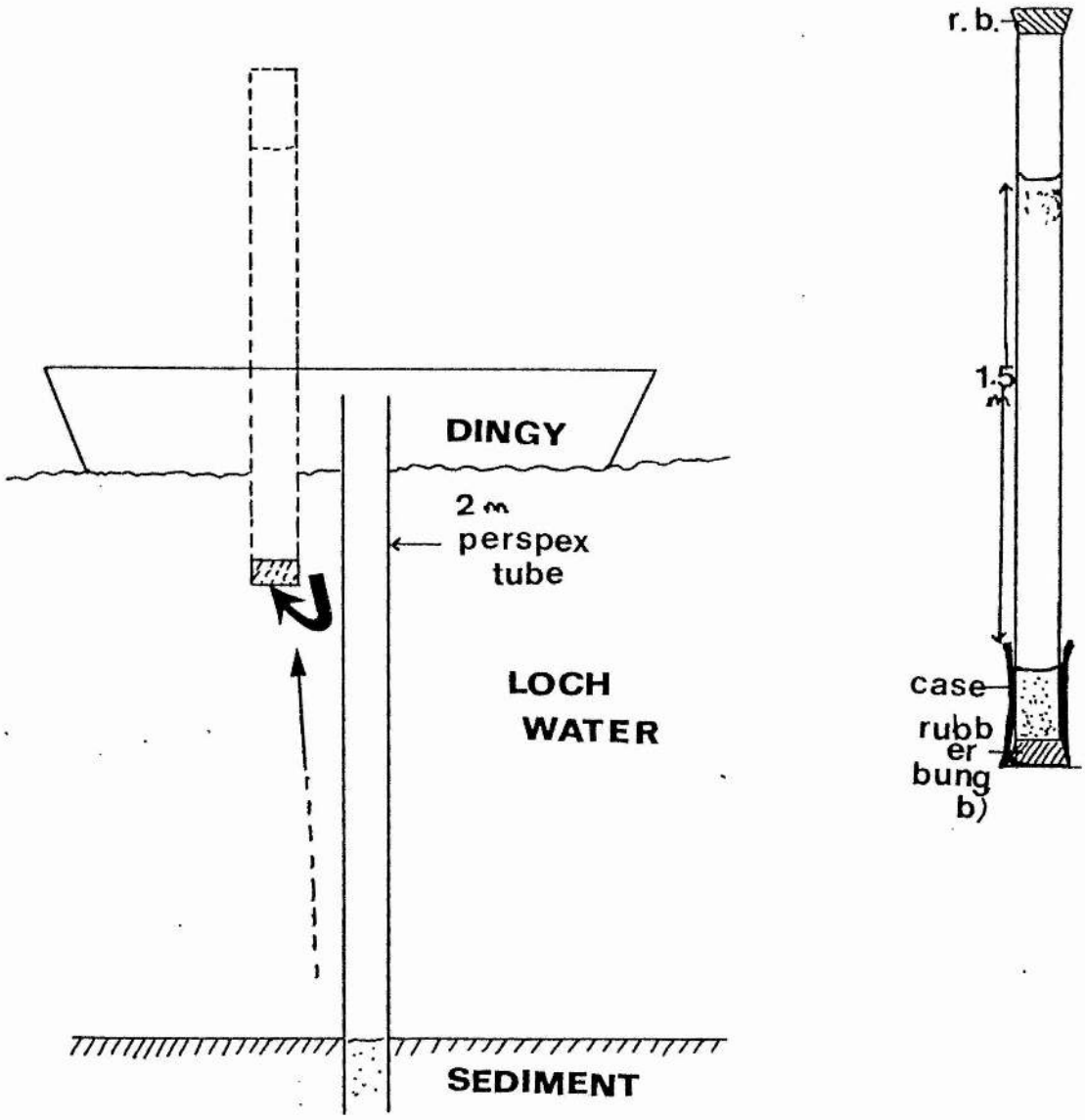

DINGY
2 m
perspex
tube
LOCH
WATER
SEDIMENT
r. b.
1.5
m
case
rubb
er
bung
b)

FIG. 3.4

One of the tubes was constantly aerated and the other tube was sealed off from the atmosphere by plugging the upper end with a rubber bung. On 25 April 1981, exactly one month later, readings were taken from 1 cm and 50 cm above the sediment surface in each tube.

2.6 Effects of added duck droppings.

In order to examine the effect of duck droppings on the water-mud interface and then the overlying water, two 0.75 m long perspex tubes were each filled with 500 g of fresh Loch Kilconquhar sediments. Then 1 l distilled water was carefully poured into each tube.

One of the tubes was aerated and the other one was sealed. Both tubes were placed in the water bath at a constant temperature of 15°C.

After one week and for five further weeks, 10 g duck droppings were added to each tube. Measurements were made weekly, before the next sample of droppings was added. Readings were taken from 1 cm, 3 cm, 5 cm and 7 cm above the sediment-water interface, by carefully siphoning out the samples. Subsequently distilled water was added to each tube to ensure the volume was always 1 litre.

2.7 The rate of nutrient release from different materials

To observe the rate of nutrient release under anoxic conditions from a) 10 g of sediment, b) 10 g sediment with 1 g of duck dropping added, c) 10 g duck droppings and d) 10 g of gull droppings, four 20 cm long polythene tubes with a diameter of 3 cm were used.

To each tube with its appropriate sample 100 ml distilled water was slowly added. Readings were taken at five intervals by piercing the tube with a needle at exactly 1 cm above the material. The solution inside the tube was drawn out by a B.D. plastipak 10 ml (Figure 3:5).

FIGURE 3:5

(opposite)

The polythene tube was pierced by a needle and the solution was drawn out by B-D plastipak 10 ml syringe for further analysis.

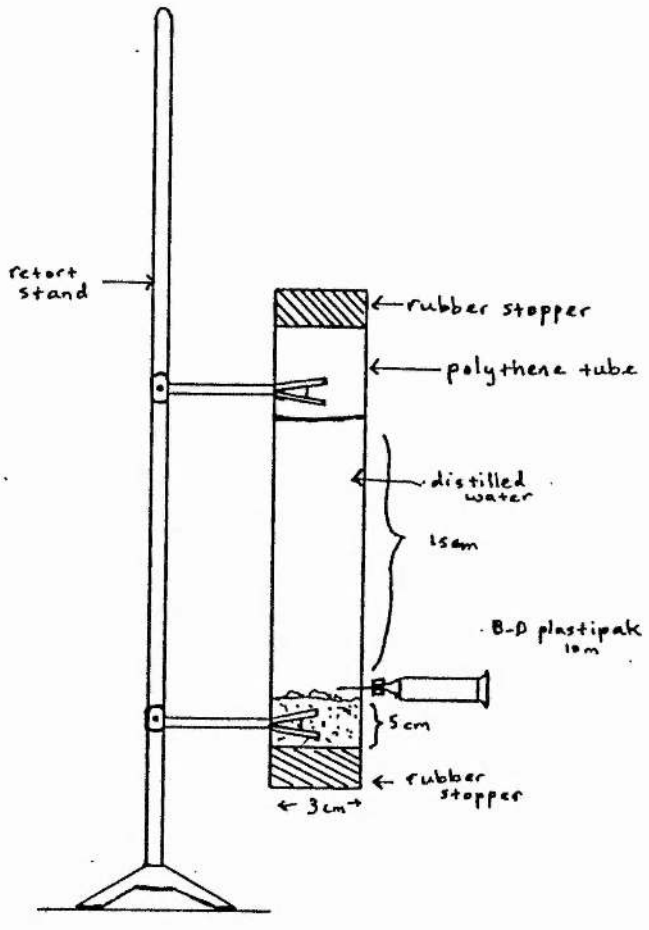

retort stand
rubber stopper
polythene tube
distilled water
15cm
B-D plastipak 10ml
5cm
rubber stopper
3cm

FIG. 3:5

3 . 2) RESULTS

2.1 Dissolved oxygen in summer

The changes in DO concentrations, soluble phosphate concentrations and pH values which were recorded over periods of 24 hours during summer and early autumn 1980 in Loch Kilconquhar are shown in Table 3:1 and Figure 3:6.

The DO concentration in the water was normally low at night and moderately high during the day. On the other hand, the soluble phosphate concentrations were always slightly higher at night and lower by day.

2.2 Hourly changes in DO concentrations

The differences in DO concentrations during night and day in the loch water are shown in more detail in Table 3:2, a-b and Figure 3:7, a-b. The readings were taken with an oxygen meter connected to the chart recorder monitored over 18 h periods.

Figure 3:7 a shows that the maximum DO concentration read of 13.4 mg/l was at 4 p.m. (1600 hrs) in the afternoon, while the minimum DO concentration reading, 2.5 mg/l, was at 5 a.m. (0500 hrs) in the early morning.

Figure 3:7b also shows that the DO readings were generally high during the day but gradually decreased during the night to a minimum value of 0.35 mg/l at 2 a.m. (0200 hrs.).

2.3 Oxygen produced by submerged macroyphytes and algal bloom

It is well known that submerged macrophytes and algae

TABLE 3:1

Changes in dissolved oxygen concentrations, soluble phosphate concentrations and pH in Loch Kilconquhar over a 24 hour period in summer and early autumn 1980.

Date	Time	Dissolved oxygen concentration (DOC) mg/l	Soluble Phosphate mg/l	pH	Observation
2 July 1980	1800	13.4 ± 0.1	0.56	8.71	After the Anabaena blooms collapsed
to					
3 July 1980	0600	3.6 ± 0.2	0.71	7.74	
16 July 1980	1200	8.2 ± 0.1	0.48	8.26	Massive growth of submerged
to	1800	20.0 ± 0.1	0.38	9.50	macrophytes
17 July 1980	2400	16.2 ± 0.1	0.44	9.31	
	0600	6.1 ± 0.1	0.49	8.72	
20 Aug. 1980	1200	7.8 ± 0.2	0.122	7.95	Aphanizomenon started to grow
to	1800	11.5 ± 0.1	0.121	7.08	
21 Aug. 1980	2400	5.2 ± 0	-	-	
	0600	4.3 ± 0.1	0.130	7.79	
26 Aug. 1980	1200	7.0 ± 0.1	0.141	8.12	Massive Aphanizomenon bloom
to	1800	9.5 ± 0.1	0.130	8.13	
27 Aug. 1980	2400	2.5 ± 0	-	-	
	0600	6.5 ± 0.1	0.146	7.73	
3 Sept. 1980	1200	7.4 ± 0.1	0.072	7.65	Aphanizomenon bloom seemed to
to	1800	9.0 ± 0.1	0.058	7.69	subside
4 Sept. 1980	2400	3.8 ± 0.1	-	-	
	0600	4.2 ± 0.1	0.080	7.60	

FIGURE 3:6

(opposite)

The changes in a) dissolved oxygen concentrations and b) soluble phosphate concentrations, at 1800 h (----- = note; high in dissolved oxygen and low in soluble phosphate) and at 0600 h (——— = note; low in dissolved oxygen and slightly high in soluble phosphate), in Loch Kilconquhar during summer and early autumn 1980. Readings derived from Table 3:1.

FIG. 3:6

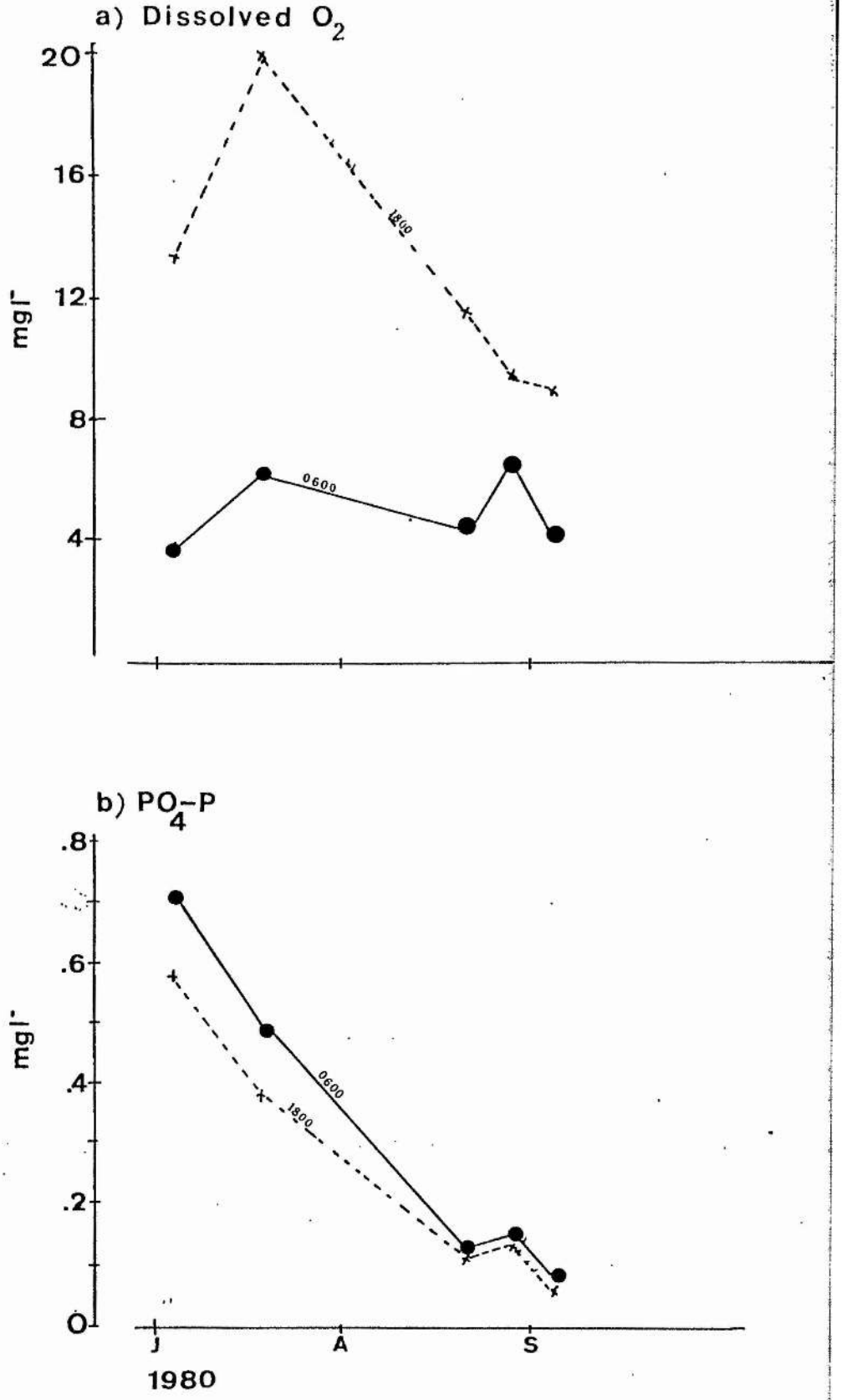

a) Dissolved O_2
20
16
12
8
4
mgl⁻
1800
0600
b) PO_4-P
.8
.6
.4
.2
0
mgl⁻
0600
1800
J
A
S
1980

TABLE 3:2a

The hourly changes in DO cons. mg/l taken over an 18 hour period from 20 Aug. 1980 to 21 Aug. 1980. At the time, an Aphanizomenon bloom was beginning.

Date	Time hrs.	Dissolved oxygen concentration (DOC) mg/l
20 Aug. 1980 to 21 Aug. 1980	1200	7.8
	1300	9.0
	1400	12.0
	1500	13.0*
	1600	13.4*
	1700	12.6
	1800	11.7
	1900	10.0
	2000	9.0
	2100	8.7
	2200	7.0
	2300	6.0
	2400	5.0
	0100	6.8
	0200	5.5
	0300	4.2
	0400	3.1*
	0500	2.5*
	0600	4.2

* minimum and maximum values.

TABLE 3:2b

The hourly changes in DO cons. mg/l taken over an 18 hour period from 26 Aug. 1980 to 27 Aug. 1980 in the midst of Aphanizomenon bloom.

Date	Time hrs.	Dissolved oxygen concentration (DOC) mg/l
26 Aug. 1980 to 27 Aug. 1980	1200	7.0
	1300	9.8
	1400	10.1*
	1500	10.5*
	1600	9.0
	1700	8.0
	1800	9.5
	1900	9.0
	2000	6.5
	2100	5.0
	2200	4.8
	2300	4.0
	2400	2.5
	0100	1.0
	0200	0.35*
	0300	1.3
	0400	1.2
	0500	2.4
	0600	6.5

* minimum and maximum values

FIGURE 3:7

(opposite)

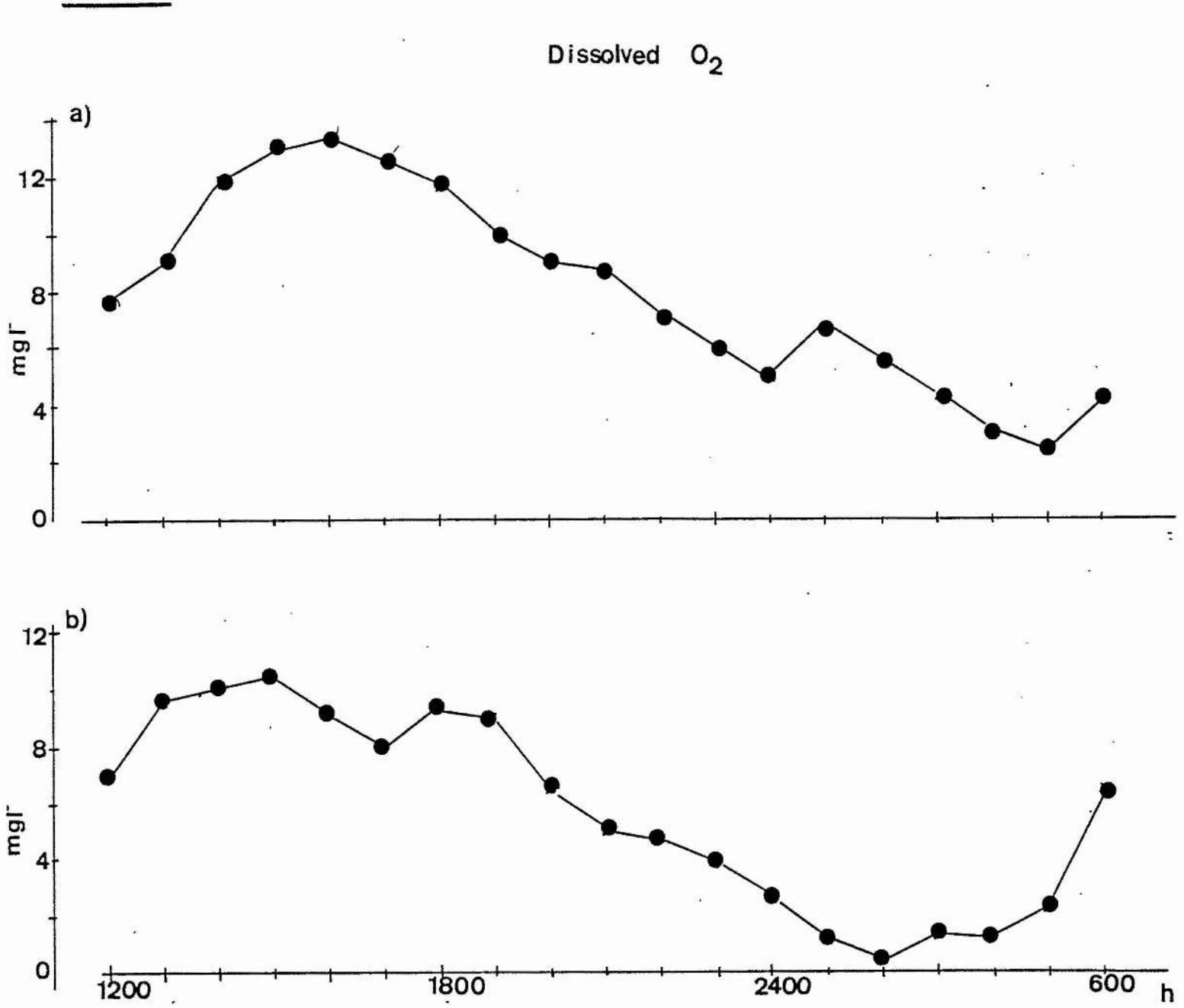
The hourly changes in DO concentrations

a) taken on 20 Aug. 1980 to 21 Aug. 1980 and

b) taken on 26 Aug 1980 to 27 Aug. 1980.

The readings are derived from Table 3:2 a-b.

FIG. 3:7



increase the DO concentration in the water during the day by photosynthesis. Table 3:3a shows that the macrophytes could produce a substantial amount of DO in 24 hours, and Table 3:3b further indicates that the net amounts of oxygen produced in one hour by one gram of fresh Zannichellia pulastris, Cladophora fracta and Myriophyllum spicatum are, respectively, 0.446, 0.594 and 0.627 mg/l.

Table 3:4a shows that an Anabaena bloom could produce 2.10 mg/l dissolved oxygen within 24 hours at 15°C and at the same temperature a Stephanodiscus bloom could produce 3.00 mg/l dissolved oxygen within 24 hours.

2.4 Two-meter perspex tube (nutrient release)

Results of the experiment on nutrient release from the sediment into the loch water, which was run for 80 days in the laboratory under anoxic conditions, are shown in Table 3:5 and Figure 3:8. These data indicate that when the DO concentrations dropped below 1 mg/l at the mud-water surface, substantial amounts of soluble phosphate and soluble nitrate were released from the sediment into the overlying water. It should be noted that the experiment was conducted in winter when ambient room temperature was low, around 10°C to 12°C.

2.5 0.75 m perspex tube (nutrient release)

The redox potential, DO concentration, soluble phosphate concentration, soluble nitrate concentration, ammonia concentration, conductivity, pH and water temperature are shown in Table 3:6. The readings were taken from 1 cm and 50 cm

TABLE 3:3a

The evolution of dissolved oxygen concentration (DOC) from 1 gm of a) Myriophyllum spicatum, b) Cladophora fracta and c) Zannichellia pulastris, over a period of 24 hrs. at 15°C (natural light).

Species	Initial DOC mg/l (C_1)	Final DOC mg/l (C_3) exposed to light (≏ 18 hrs. May 1980)	DOC mg/l evolved C_3-C_1 in 24 hrs.
Myriophyllum spicatum	4.6±0.1	17.8±0.1	17.8 - 4.6 = 13.2
Cladophora fracta	4.6±0.1	17.6±0.5	17.6 - 4.6 = 13.0
Zanichellia pulastris	4.6±0.1	11.5±0.1	11.5 - 4.6 = 6.9

Table 3:3b

The estimation of net photosynthesis (nP) and gross photosynthesis (gP).

Species	Final DOC mg/l (C_2) kept in the dark (24 h)	nP (C_3-C_1)/hr O_2 mg/g/hr	gP (C_3-C_2)/hr O_2 mg/g/hr
Myriophyllum spicatum	2.8±0.2	0.550	0.627
Cladophora fracta	3.4±0.5	0.542	0.594
Zannichellia pulastris	0.8±0.1	0.288	0.446

TABLE 3:4a

The evolution of dissolved oxygen concentration (DOC) mg/l from an Anabaena bloom (357 mg/m^3 Chl a) over a period of 24 hrs. at 15°C, in summer 1980 (natural light).

Initial DOC mg/l (C_1)	Final DOC mg/l (C_3) exposed to light ($\triangleq$ 19 hrs; June 1980)	DOC mg/l evolved C_3-C_1 in 24 hrs.
5.70 15 May 1980	7.80 16 May 1980	7.80 - 5.70 = 2.10

TABLE 3:4b

The evolution of dissolved oxygen concentration (DOC) mg/l from Stephanodiscus blooms (136 mg/m^3 Chl a) over a period of 24 hrs. at 15°C, in winter 1980 (natural light).

Initial DOC mg/l (C_1)	Final DOC mg/l (C_3) exposed to light ($\triangleq$ 8 hrs; January 1980)	DOC mg/l evolved C_3-C_1 in 24 hrs.
7.7 23 January 1980	10.7 24 January 1980	10.7 = 7.7 = 3.0

Table 3:5

Comparative measurements over an interval of 80 days in the 1.5 m deep tube water column and sediment. The initial readings were taken in the loch itself (6 Nov. 1979) and the final readings were taken in the laboratory (25 Jan. 1980), after being sealed off from the atmosphere for 80 days.

Analysis	Depth	Initial 6 Nov. 1979	Final 25 Jan. 1980
$[PO_4 - P]$ mg/l	0	0.39	1.18
	0.5	0.34	1.15
	1.0	0.35	1.20
	1.5	0.08	1.20
$[NO_3 - N]$ mg/l	0	1.50	2.50
	0.5	1.55	2.50
	1.0	1.45	2.55
	1.5	1.49	2.50
DO cons. mg/l	0	10.2	0.10
	0.5	10.1	0.05
	1.0	10.0	0.01
	1.5	10.0	0.00
pH	0	8.0	7.8
	0.5	8.0	7.8
	1.0	8.0	7.6
	1.5	7.9	7.6

FIGURE 3:8

(opposite)

Comparative measurements over an interval of 80 days in the experimental sediment-water systems. The 2 m perspex tube was sealed off from the atmosphere for 80 days.

a) The initial readings which were taken in the Loch at Station B on 6 Nov. 1979.

b) The final readings which were taken after 80 days on 25 Jan. 1980.

FIG. 3:8

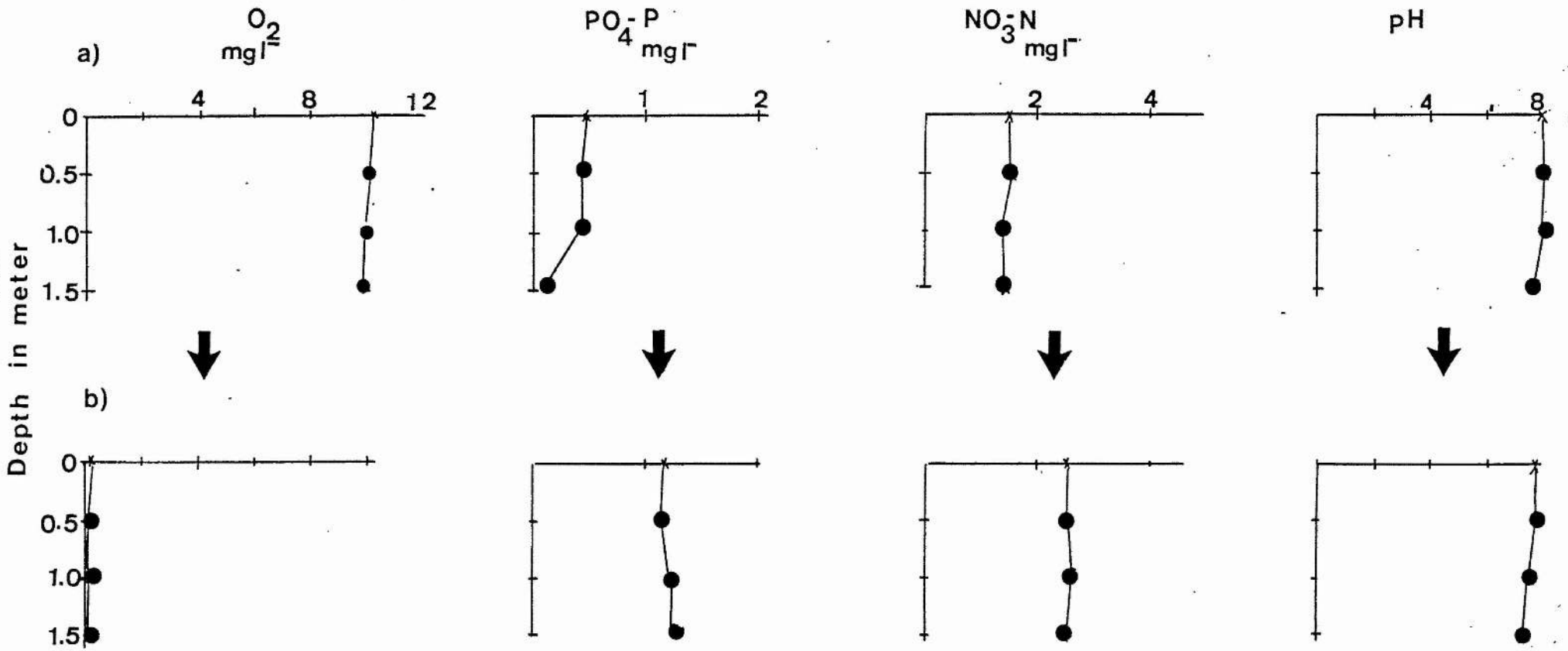

a)
b)
O_2 mg l^{-1}
PO_4-P mg l^{-1}
NO_3-N mg l^{-1}
pH
4
8
12
1
2
4
4
8
0
0.5
1.0
1.5
Depth in meter

TABLE 3:6

Redox potential E_7 and analytical data from Loch Kilconquhar water drawn from 1 cm above the sediment in sealed and open 0.75 m perspex tubes. The initial readings were taken from the loch itself, and the final reading after one month.

	Initial reading of Loch Kilconquhar water 25 March 1981	Final reading of Loch Kilconquhar water in the open tube 25 April 1981	Final reading of Loch Kilconquhar water in the sealed tube 25 April 1981
Redox potential E_7 (mV)	330	324 326 (50 cm)*	240 260 (50 cm)*
DO mg/l	12.5±0.1	7.5±0.1 8.2±0.10 (50 cm)*	0.9±0.1 1.2±0.1 (50 cm)*
$[PO_4\text{-}P]$ mg/l	0.018	0.380 0.370 (50 cm)*	0.880 0.830 (50 cm)*
$[NO_3\text{-}N]$ mg/l	1.02	1.85	1.55
$[NH_4\text{-}N]$	0.11	0	2.0
Conductivity umhos	495	530	540
Alkalinity meg/l	2.70	4.60	4.20
pH	8.24	8.20	7.19
Water temperature °C	8°C	14°C	14°C

note: * = 50 above the sediment

above the sediment-water interfaces from the 0.75 m perspex tubes.

Generally it is relatively difficult to take the reading of DO concentration above the mud, particularly when the concentration is low. It is more convenient to use redox potential in place of dissolved oxygen in this particular case. Figure 3:9 shows a possible correlation between the redox potential and dissolved oxygen concentration ($y = 8.21 x + 245$; $r = 0.89$) and Figure 3:10 shows the correlation between DO concentration and soluble phosphate concentration ($y = -0.073 x + 0.942$; $r = 0.9985$).

2.6 Effects of added duck droppings

The effect of duck droppings in distilled water under aerobic and anaerobic conditions are shown in Table 3:7. Figure 3:11a shows that the redox potentials were reasonably low in the anaerobic condition compared with the aerobic condition (aerated tube). Figure 3:11b shows that the soluble phosphate was generally high in the aerated tube compared with the anaerobic tube.

On the other hand, the conductivity and the soluble nitrate concentration were high in the anaerobic tube compared with the aerobic tube which is shown in Figure 3:11c and Figure 3:11d.

2:7 The rate of nutrient release from different materials

The comparative studies on the fall of redox potentials in anaerobic conditions and the release of nutrients which was observed from a) Loch Kilconquhar sediment; b) Loch

FIGURE 3:9

(opposite)

A possible correlation between redox potential E_7 in mVol+ and dissolved oxygen concentrations in mg/l. Readings were derived from Table 3:5 (0.75 m perspex tubes).

FIG. 3:9

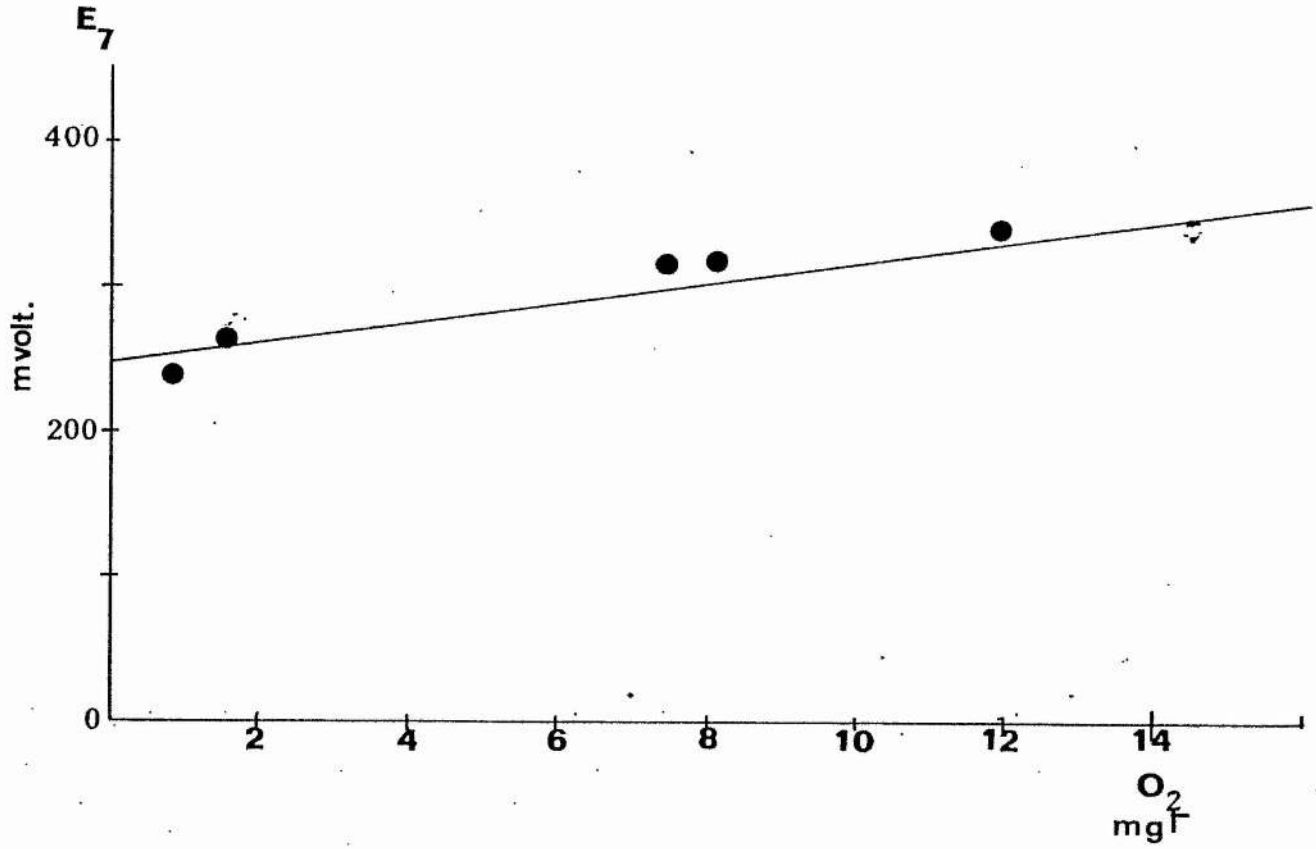


FIGURE 3:10

(opposite)

A correlation between dissolved oxygen concentration and soluble phosphate concentration in a laboratory experiment (0.75 m perspex tubes). Readings were derived from Table 3:5.

FIG. 3:10

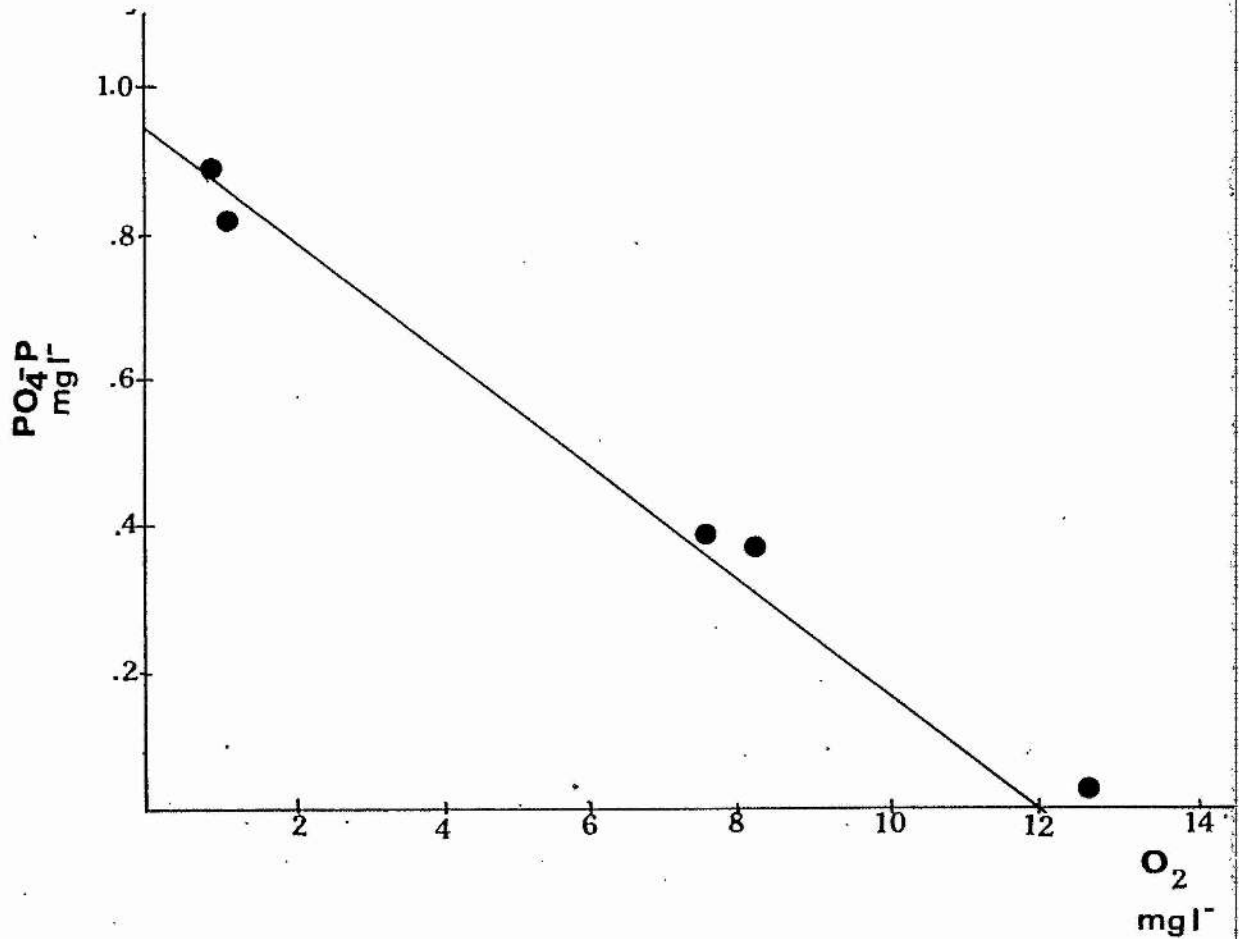


TABLE 3:7

Effects of weekly added 10g duck droppings on 1 l distilled water with ≙ 500 g of Loch Kilconquhar sediment in a) an aerated perspex tube and b) a sealed perspex tube. Readings were taken at 1 cm, 3 cm, 5 cm and 7 cm above the water-sediment interface, at the controlled temperature of 15°C.

	Initial reading 18 Feb. 1981	Depth in cm	17 March 1981		14 March 1981		31 March 1981		6 April 1981		14 April 1981		21 April 1981		28 April 1981	
			(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Potential E_7 mV	350	1	325	150	300	130	325	200	325	190	310	200	310	210	320	230
		3	325	160	300	125	325	210	325	200	310	210	310	220	325	250
		5	330	160	310	110	330	210	330	200	320	220	320	220	325	250
		7	335	175	325	105	330	220	330	200	320	220	320	220	330	250
PO_4-P mg/l	0	1	0.36	0.62	2.60	2.20	4.00	3.00	3.80	1.50	2.50	2.00	3.40	2.50	2.60	3.00
		3	0.38	0.74	2.20	2.80	4.50	2.50	4.40	1.60	2.50	2.00	3.30	3.00	3.00	3.20
		5	0.38	0.78	2.40	2.20	3.40	2.80	4.00	2.00	1.80	1.60	3.20	2.80	2.60	3.40
		7	0.37	0.76	2.20	3.20	3.20	2.40	3.50	1.90	2.00	2.00	3.20	3.00	1.00	3.00
NO_3-N mg/l	0	1	1.50	9.00	4.00	10.00	5.40	14.00	7.50	12.00	8.00	9.00	10.5	8.00	10.00	11.2
		3	1.50	8.00	3.50	9.95	6.40	13.00	8.00	12.50	8.00	10.00	10.0	7.50	11.50	8.0
		5	1.55	8.50	5.50	9.95	6.00	14.40	8.00	12.50	10.00	10.00	9.0	6.00	11.50	9.0
		7	1.60	8.50	5.60	10.20	7.00	14.50	7.50	12.50	9.00	12.50	10.0	5.50	11.00	8.5
NH_4-N mg/l	0		-	-	-	-	-	-	2.80	1.80	-	2.00	0.1	0.80	0.80	2.80
									3.00	1.40		3.50	0.1	1.00	0	3.00
									2.10	1.20		3.00	0	1.00	0	3.50
									2.00	1.20		3.50	0	1.50	0	2.80
Conductivity µmhos	-	1	520	3100	530	2200	530	2300	530	1500	500	1350	500	900	355	1200
pH	5.5	1	8.2	6.4	7.8	6.5	7.8	5.2	8.1	6.8	8.0	7.0	8.0	7.2	8.0	7.4
Alkalinity meg l^{-1}	-	1	2.9	-	3.5	-	3.5	-	3.6	-	3.0	-	3.0	-	3.2	-

FIGURE 3:11

(opposite)

a) The redox potential and b) the changes in soluble phosphate concentrations in an aerated 0.75 m perspex tube (——) and an anaerated 0.75 m perspex tube (----). Each tube was weekly added with 10 g of duck droppings.

FIG. 3:11(a&b)

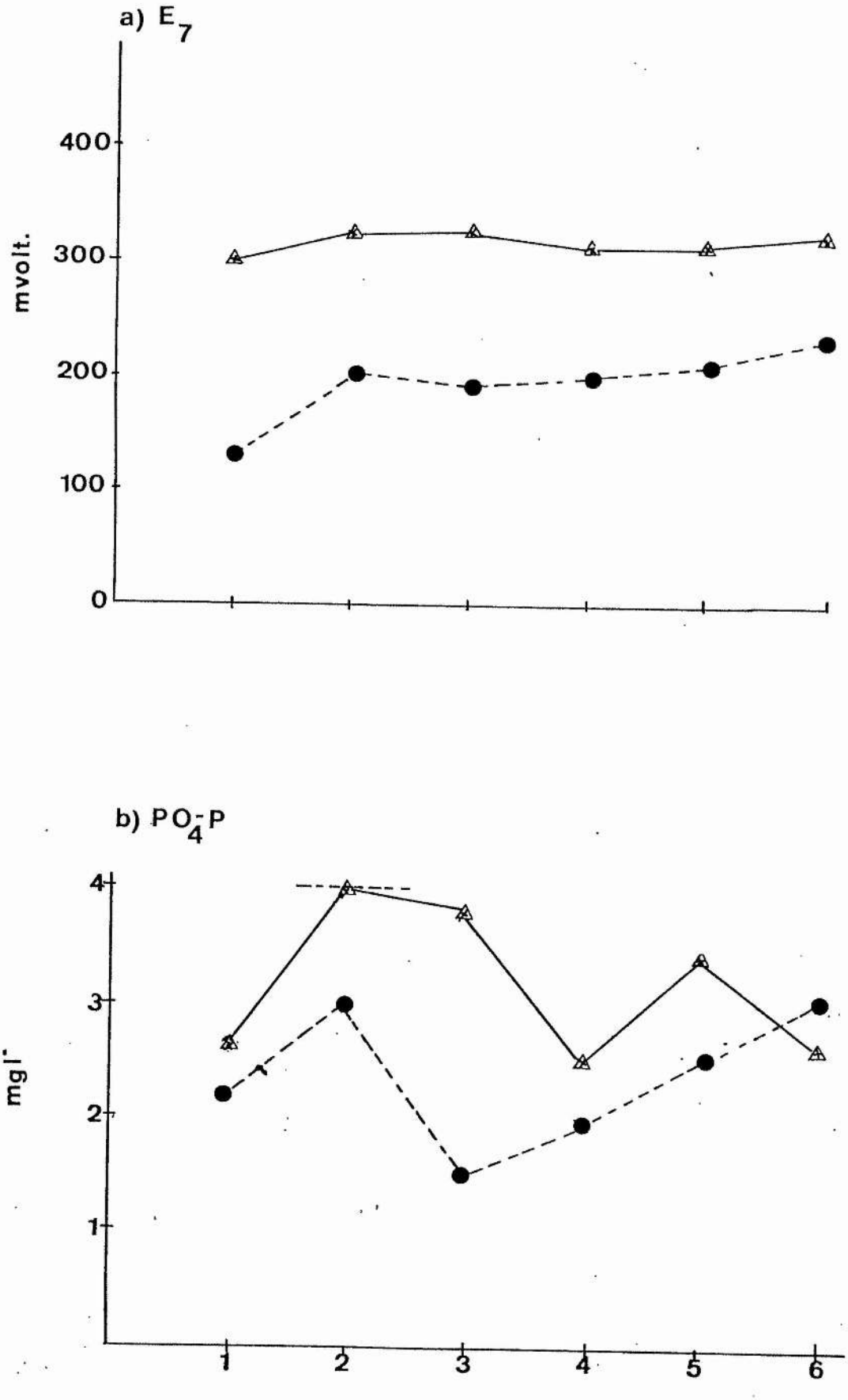
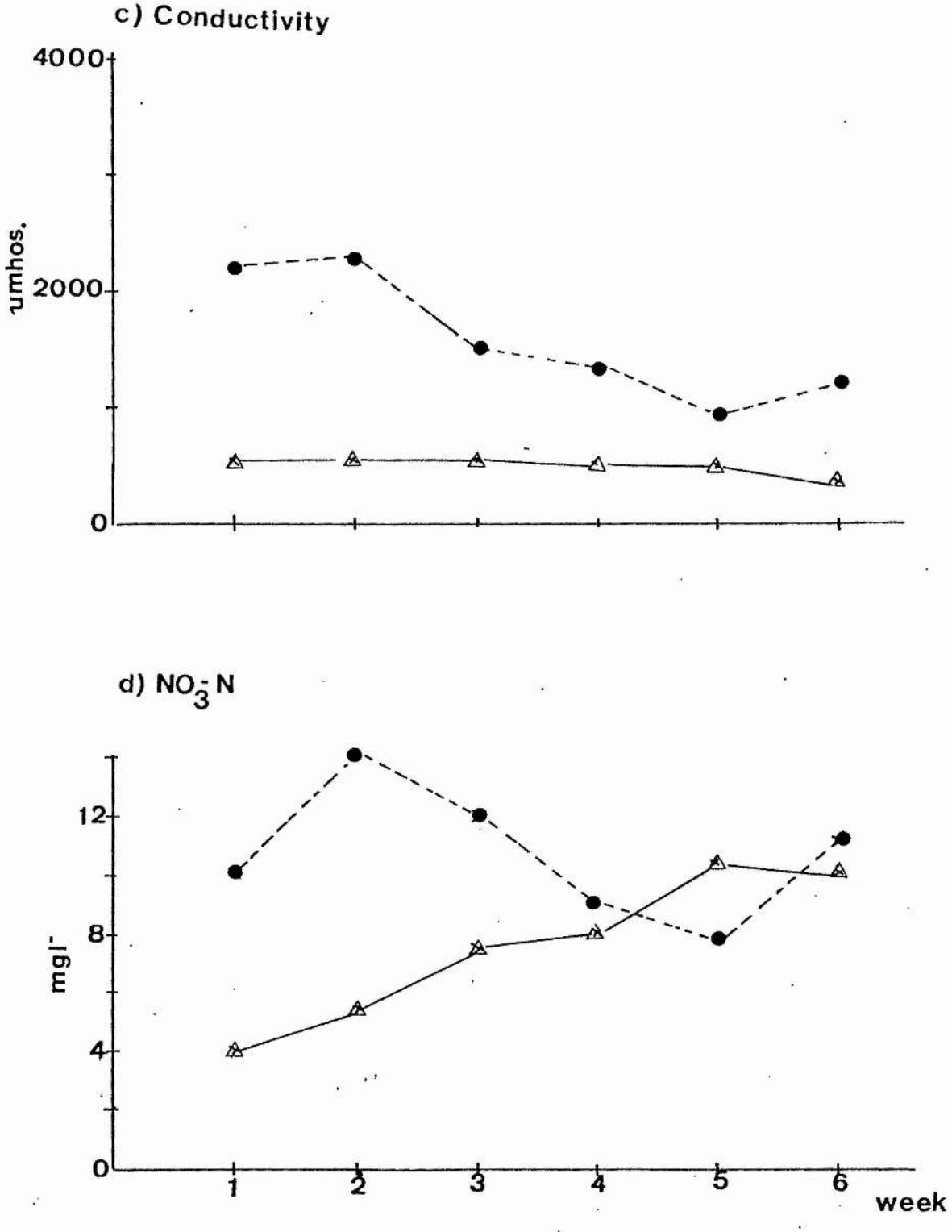


FIGURE 3:11

c) The conductivities in umhos and d) the soluble nitrate concentrations in an aerated 0.75 m perspex tube (——) and an anaerated 0.75 m perspex tube (----). Both of the tubes were subjected to 10 of duck droppings weekly.

FIG. 3:11(c&d)


c) Conductivity
4000
2000
0
umhos.
d) NO_3^-N
12
8
4
0
mgl⁻
1
2
3
4
5
6
week

Kilconquhar sediment added with a duck dropping; c) 10 grams of duck droppings, and d) 10 grams of gull droppings are shown in Table 3:8a and 3:8b.

Figure 3:12a shows that with the addition of 1 gm of duck dropping to the loch sediment, the redox potential subsequently dropped and Figure 3:12b also shows that at the same time, the nutrient concentrations in the water were higher than that of the loch sediment.

The redox potentials dropped below the transition level of $E_7$240 mV for the duck and the gull droppings are shown in Figure 3:12c, and at the same time there was a release of large quantities of nutrients in the overlying water, as shown in Figure 3:12d.

TABLE 3:8a

Effect on redox potentials with time in 100 ml distilled water at 1 cm above the surface of a) 10 gm sediment from Loch Kilconquhar and b) 10 gm sediment from Loch Kilconquhar with added duck dropping (1 gm). The experiments were conducted in anaerobic conditions in the sealed polythene tubes at the temperature of 15°C.

	12/3/81		17/3/81		22/3/81		27/3/81		1/4/81		6/4/81	
	a)	b)	a)	b)	a)	b)	a)	b)	a)	b)	a)	b)
Redox potential E_7 (mV)	260	170	255	170	250	180	250	190	250	200	250	210
$[PO_4\text{-}P]$ mg/l	0.001	5.00	0.01	3.80	0.08	2.00	0.20	0.90	0.10	1.00	0.12	1.10
$[NO_3\text{-}N]$ mg/l	3.40	7.20	2.00	6.00	1.60	4.00	1.40	3.00	1.20	3.00	1.30	4.00
$[NH_4\text{-}N]$ mg/l	-	-	-	-	-	-	-	-	-	-	0.20	1.40

TABLE 3:8b

Effect on redox potentials with time in 100 ml distilled water at 1 cm above the surface of c) 10 gm of fresh duck droppings and d) 10 gm of fresh gull droppings. The experiments were conducted in anaerobic conditions in the sealed polythene tubes at the temperature of 15°C.

	12/3/81		17/3/81		22/3/81		27/3/81		1/4/81		6/4/81	
	c)	d)	c)	d)	c)	d)	c)	d)	c)	d)	c)	d)
Redox potential E_7 (mV)	220	180	210	190	220	200	200	200	200	200	190	220
$[PO_4\text{-}P]$ mg/l	2.40	5.80	21.40	4.60	2.80	4.20	5.80	3.60	3.80	3.40	4.20	4.60
$[NO_3\text{-}N]$ mg/l	4.00	17.40	5.00	12.60	4.20	8.00	8.00	10.00	6.40	11.00	6.00	11.50
$[NH_4\text{-}N]$ mg/l	-	-	-	-	-	-	-	-	-	-	4.20	6.20

FIGURE 3:12a

(opposite)

The release of soluble phosphate and soluble nitrate concentrations into the overlying distilled water from a loch sediment (——) and a loch sediment added with duck dropping (----). This was due to the drop in redox potential. (Initial readings were taken after five days.)

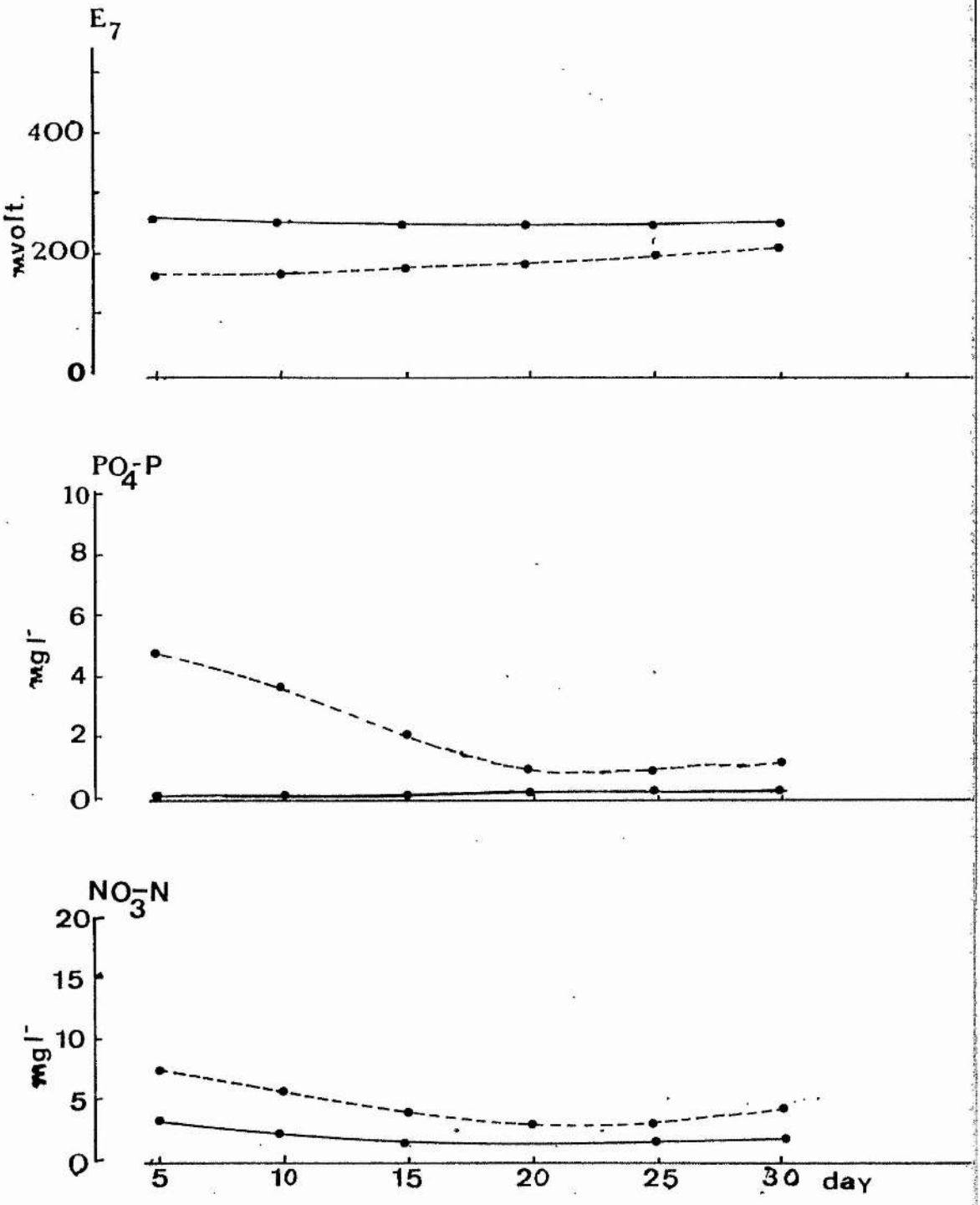

E_7
400
200
0
mvolt.
PO_4-P
10
8
6
4
2
0
mg l⁻
NO_3-N
20
15
10
5
0
mg l⁻
5
10
15
20
25
30
day

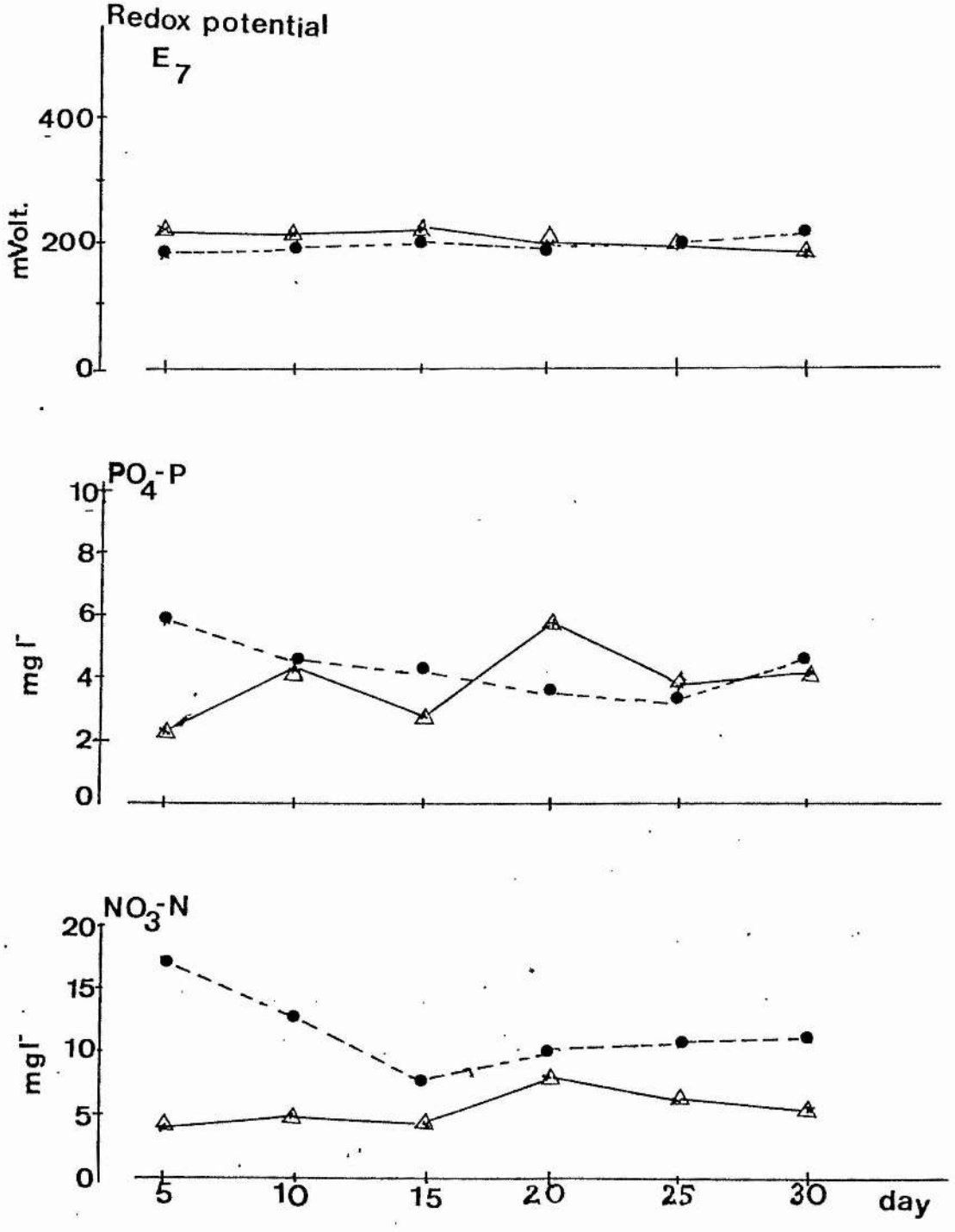
FIG. 3:12 a)

FIGURE 3:12b

(opposite)

The release of soluble phosphate and soluble nitrate concentrations into the distilled water from duck droppings (——) and gull droppings (----). This is due to the drop in redox potentials.

FIG. 3:12 b)


Redox potential
E_7
400
200
0
mVolt.
PO_4-P
10
8
6
4
2
0
mg l⁻
NO_3-N
20
15
10
5
0
mg l⁻
5
10
15
20
25
30
day

3 . 3) DISCUSSION

Hart et al (1976) and Slater and Boag (1978) stated that a large pool of phosphorus is stored in lake sediment which exists in a variety of forms and, under certain conditions, may undergo chemical and biological transformations. Eventually it may be released from the sediment to the water column, and thus become available for phytoplankton production.

Nutrients released from a loch sediment in this manner play a significant role in lake productivity. As observed by Slater and Boag (1978), studies in one of their lakes showed that the diversion of sewage from the lake produced no tangible improvement in algal problems or water quality until the upper layer of the sediment was removed by dredging.

In Loch Kilconquhar, during the work on this thesis it was observed that at least once a year there was a substantial nutrient release from the sediment into the loch water, in early autumn in the year 1979 and the middle of summer in the year 1980. On both occasions the release occurred after the massive collapse of algal blooms.

The decomposition of organic matter on the loch sediment started to increase rapidly in spring with the rise of temperature. According to Vamos and Tasuadi (1975) under optimal circumstances with a sufficient supply of organic materials, micro-organisms rapidly proliferate and their number may even reach more than a hundred or thousand times the original amount.

Apparently, in Loch Kilconquhar, there is an abundant amount of organic matter on the lake bottom. This is derived from bird droppings and also a sustained amount of decaying plant material, mainly from the sudden collapse of algal blooms.

The organic matter is decomposed by micro organism, which in the initial stage, creates a high oxygen demand. The final result is the development of oxygen deficit in this fertile loch, especially late at night during summer when the oxygen supplied during the day by photosynthesising phytoplankton and plants, has run out.

As we might therefore expect, in Loch Kilconquhar, such deficits have now been found mainly during the night. For example, on 28 August 1980 at 2 a.m. (0200 hrs.) the DO concentration in shallow water by the boat house fell to 0.35 mg/l compared with a saturating concentration of 10 mg/l, at 15°C water temperature.(N. Strahler and H. Strahler, 1974).

At the same time, the soluble phosphate was observed to be reasonably high during summer, particularly after the collapse of massive algal blooms. Mortimer (1971) has shown that a decline in oxygen concentration can be correlated with the transfer of substantial quantities of phosphate.

Oxygen deficits increase the rate of release of phosphate from the sediment, and sediment phosphate is enriched by bird droppings, dead phytoplankton and plants. It is also noted, however, that under anaerobic conditions in the laboratory, considerable phosphate release was inversely proportional to the drop in DO concentration ($r = -0.9985$).

The gull and duck droppings were observed to release

5.80 mg/l and 4.40 mg/l of PO_4-P into the distilled water within five days under anaerobic conditions. Such droppings can produce 1.16 mg/l and 0.88 mg/l of [PO_4-P] per day respectively, a very high release rate.

Mathias and Barica (1980) concluded that the sediment of eutrophic lakes consumed oxygen about 3 times faster (0.23 g m^{-2} d^{-1}) than those of oligotrophic lakes (0.08 g m^{-2} d^{-1}) but water column respiration was about the same (0.01 g m^{-3} d^{-1}) for both groups of lakes. This statement suggests that the depletion in oxygen is mainly due to the high utilization of oxygen in the loch sediment rather than the loch water.

Giddings (1973) stressed the importance of oxygen when he stated that whether in the atmpsphere or in the water, it creates a strong oxidizing environment. Many substances that are found in water are profoundly changed by oxidation. Reduced nitrogen exists as ammonia (NH_3) and various amines ($R-NH_2$). Oxidized nitrogen becomes the relatively docile nitrate ion (NO_3-). The partly reduced form of iron (Fe) is iron (11) ion, Fe^{2+}. Compounds of iron (11) are fairly soluble in water. Iron (111) compounds, which occur in aerobic water, are not usually soluble in the water.

The sharp decrease in DO concentration corresponded to the fall of redox potential. So far as the mud-water interface is concerned, conditions governing the Fe^{2+}/Fe^{3+} redox state are the most important. Indeed its most conspicuous regulatory feature is the oxygen content of this interface. This in turn is regulated by the rate of oxygen supply to the surface and the rate of organic decomposition. The control

ultimately is microbiological.

Two pioneers in this work, Pearsall and Mortimer (1939) pointed out that a marked fall in potential, the change-over from oxidizing to reducing conditions, only takes place at low oxygen concentrations. Mortimer (1941) and Mortimer (1942) stated that the transition point between oxidizing and reducing states is around the redox potential E_7 of 230 mVolt and DO concentration of approximately 0.5 mg/l.

As shown in Table 3:9 the redox potential on the sediment-water interface of Loch Kilconquhar is rather low compared with other lakes. This is possibly due to the highly reduced state of Loch Kilconquhar sediment, as stated before, because of the considerable amounts of organic material on it.

As indicated by Howe, Howarth, Teal and Valiela (1981) a water plant growing on a lake sediment can to a certain extent help to increase the redox potential in that environment, indirectly preventing nutrient release from a sediment, While they also observed that in places without plant growth, the redox potential in the mud was comparatively low.

It is interesting to note from Table 3:10 that the addition of duck droppings to Loch Kilconquhar sediment reduced the redox potential by 110 mVolt. The result also indicated that the potentials of duck and gull droppings were very low and always in the reduced state.

The summary of nutrients released from the Loch Kilconquhar sediment is shown in Figure 3:11. The same phenomenon was observed by Olah (1975) in a shallow over-loaded lake in Hungary. The most important point in this particular case is the initial increase of input of organic matter into the

loch. This is mainly due to the arrival of the large population of birds to this loch, maybe a decade ago or possibly more.

TABLE 3:9

Redox potential readings (E_7) taken from sediment water interfaces from various lakes.

No.	Lake	E_7 mVolt	Reference
1)	Lake George (Uganda)	+225	Viner (1975)
2)	Coolar Lake (Sinai, Israel)	+350	Cohen et al. (1975)
3)	Ennerdale Water (Lake District, England)	+510	Mortimer (1942)
4)	Crummock Water (Lake District, England)	+510	Mortimer (1942)
5)	Windermere, North Basin, (Lake District, England)	+500	Mortimer (1942)
6)	Southport pond (Canada)	+240	Hayers et al.(1958)
7)	Punch Bowl (Canada)	+300	Hayers et al. (1958)
8)	Copper Lake (Canada)	+400	Hayers et al. (1958)
9)	Lily Lake (Canada)	+350	Hayers et al. (1958)
10)	Loch Kilconquhar (Fife, Scotland) (25/3/81)	+260	1981 (this study)

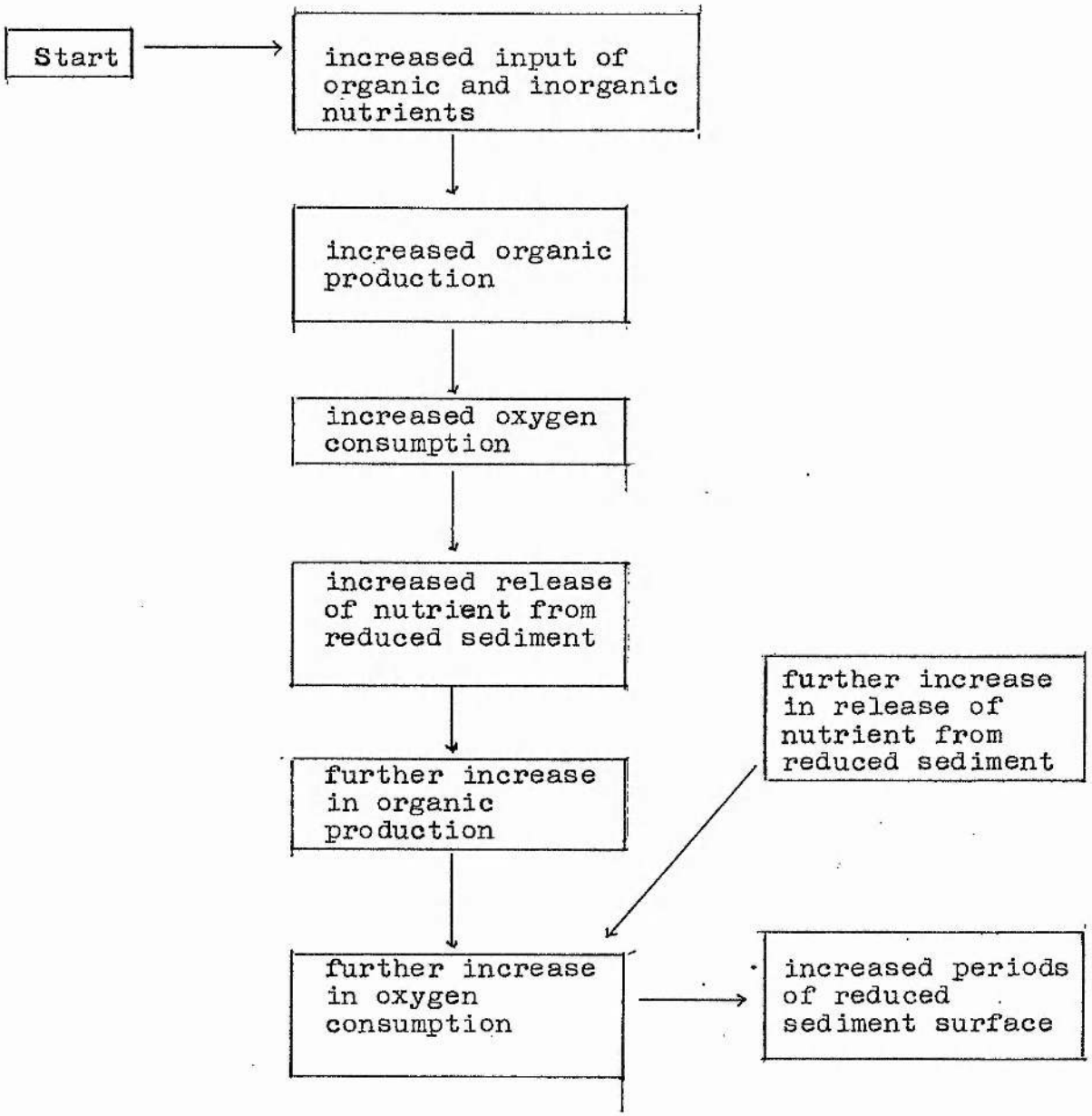
TABLE 3:10

Redox potential readings (E_7) 0.5 cm below the surface of these materials.

No.	Material	E_7 mVolt	Reference
1)	Tall Creek Bank (Spartina alterniflora)	+400	Howe et al. (1981)
2)	Short Creek Bank (Spartina alterniflora)	+250	Howe at al. (1981)
4)	Fertilized area (Great Sippewisset Salt Marsh - without plant)	+350	Howe et al. (1981)
5)	Unfertilized area (Great Sippewisset Marsh - without plant)	0	Howe et al. (1981)
6)	Loch Kilconquhar sediment	+260	1981 (this study)
7)	Loch Kilconquhar sediment with duck dropping on top	+150	1981 (this study)
8)	Duck dropping	-10	1981 (this study)
9)	Gull dropping	-30	1981 (this study)

FIGURE 3:11

The nutrient release from Loch Kilconquhar sediment.



3 . 4) CONCLUSION

The results show that dissolved oxygen is generally low in both lochs in summer. However, in Loch Kilconquhar on several occasions during the massive collapse of algal blooms, the dissolved oxygen dropped sharply to below 3.6 mg/l during the day at Station A. Further drops to below 1 mg/l were observed at night and at the same time the soluble phosphate concentration was high. It is, therefore, concluded that in Loch Kilconquhar nutrient release generally occurred at night in summer, particularly after the collapse of an algal bloom.

Results from a series of experiments in the laboratory confirmed that under anaerobic conditions, substantial amounts of nutrients could be released from Loch Kilconquhar sediment into the water, generally when the dissolved oxygen dropped below 1 mg/l and the redox potential fell to around 240 mVolt.

Substantial amounts of organic matter such as bird droppings and decaying plant materials are needed to promote bacterial activity in lake sediment and may in turn cause surface sediment to be in a reduced state. Experimental results show that bird droppings can help reduce redox potential of the sediment and therefore indirectly initiate nutrient release from that sediment.

It is concluded that bird droppings indeed play a major role in the Loch Kilconquhar ecosystem, particularly its nutrient status. Not only are they one of the major contributors of nutrient such as phosphate in the loch, but they also help regulate this nutrient cycle in the loch.

Although on several occasions ammonium-nitrogen [NH_4-N]

was analysed from both lochs, it was normally below the limit of detection, but very minute quantities were found during summer in Loch Kilconquhar. However, under anaerobic conditions and reduced states in the laboratory experiments, substantial amounts of NH_4-N was found in the water.

GENERAL CONCLUSIONS

GENERAL CONCLUSIONS

Phosphate and algal blooms

It is concluded that phosphate, particularly in the soluble form is the single most essential nutrient in freshwater and that its presence will obviously have a significant effect on overall lake productivity. Thus in Loch Kilconquhar the successive occurrences of algal blooms in summer and autumn 1980 were mainly due to the continuing high soluble phosphate concentrations in the loch water.

To trigger a massive blue green algal growth in the warm conditions of spring at least 0.01 mg/l soluble phosphate is needed. Since, however, the soluble phosphate concentration in Loch Kilconquhar was already well above that threshold, the Anabaena bloom appeared much earlier in the season.

Another interesting point is the occurrence of a Stephanodiscus bloom in winter when most of the loch was intermittently frozen. This clearly indicates that, with an ample supply of nutrients, particularly phosphate and silica, this diatom grows well in spite of low water temperature and light intensity, and short days.

On the other hand, no blue green algal bloom occurred in Loch Lindores in 1980. This is contrary to expectation for an apparently eutrophic loch. Although the loch was reasonably high in other nutrients such as nitrate, the soluble phosphate concentrations were generally small and, most of the time, below the limit of detection, especially in spring 1980. These points strongly suggest that low phosphate concentration is the factor preventing blue green algal blooms occurring

in this loch.

Source of phosphate in Loch Kilconquhar

From the results and references cited in Chapter 2, it is concluded that duck and gull droppings which are rich in phosphate, are a major source of this nutrient in Loch Kilconquhar. (However, a small quantity of phosphate is also brought down by the inflow, which drains from the arable land into the loch.)

The daily excretion from these birds is mostly sedimented on the loch bottom, but a small percentage is directly soluble in water, particularly from the gull. Eventually and probably in part as a result of highly labile organic matter contributed by these bird droppings, the sediment becomes intermittently anaerobic in summer, thus facilitating the observed phosphate release.

From the above facts, Loch Kilconquhar appears to be affected by a rate of natural eutrophication which is similar to cultural eutrophication. So it is not surprising that this loch shows signs of "ageing" (over-eutrophication) with frequent occurrence of undesirable blooms and massive growth of water plants associated elsewhere with "cultural enrichment".

Phosphate release from Loch Kilconquhar sediment

The massive Anabaena bloom which formed a thick suspension in the surface layer and almost covered the entire loch surface in summer, due to the unfavourable circumstances started to collapse and decay.

The sudden collapse of this algal bloom had caused a

large-scale depletion of oxygen in the loch. As a result the DO concentrations were particularly low at this time of the year and reached a minimum of 3.5 mg/l during the day on 3rd July 1980.

At the same time, the soluble phosphate concentration was particularly high in the loch water. Similar results were also obtained from a series of experiments done in the laboratory, in which it leads to a possible conclusion that the drop of DO concentration to 1 mg/l or less, and the fall of redox potential E_7 to 240 mVolt or below will result in the substantial release of phosphate from the loch sediment into the water.

It should be concluded that the dense bird populations have played a significant role in the enrichment of Loch Kilconquhar. They help to fertilize the loch through their droppings and also help to initiate the nutrients released from the loch sediment (Figure 4:1).

FIGURE 4:1

(opposite)

The phosphate cycle in Loch Kilconquhar. It should be noted that phytoplankton can only utilize phosphate in the form of SRP (Soluble Reactive Phosphate; orthophosphate PO_4-P).

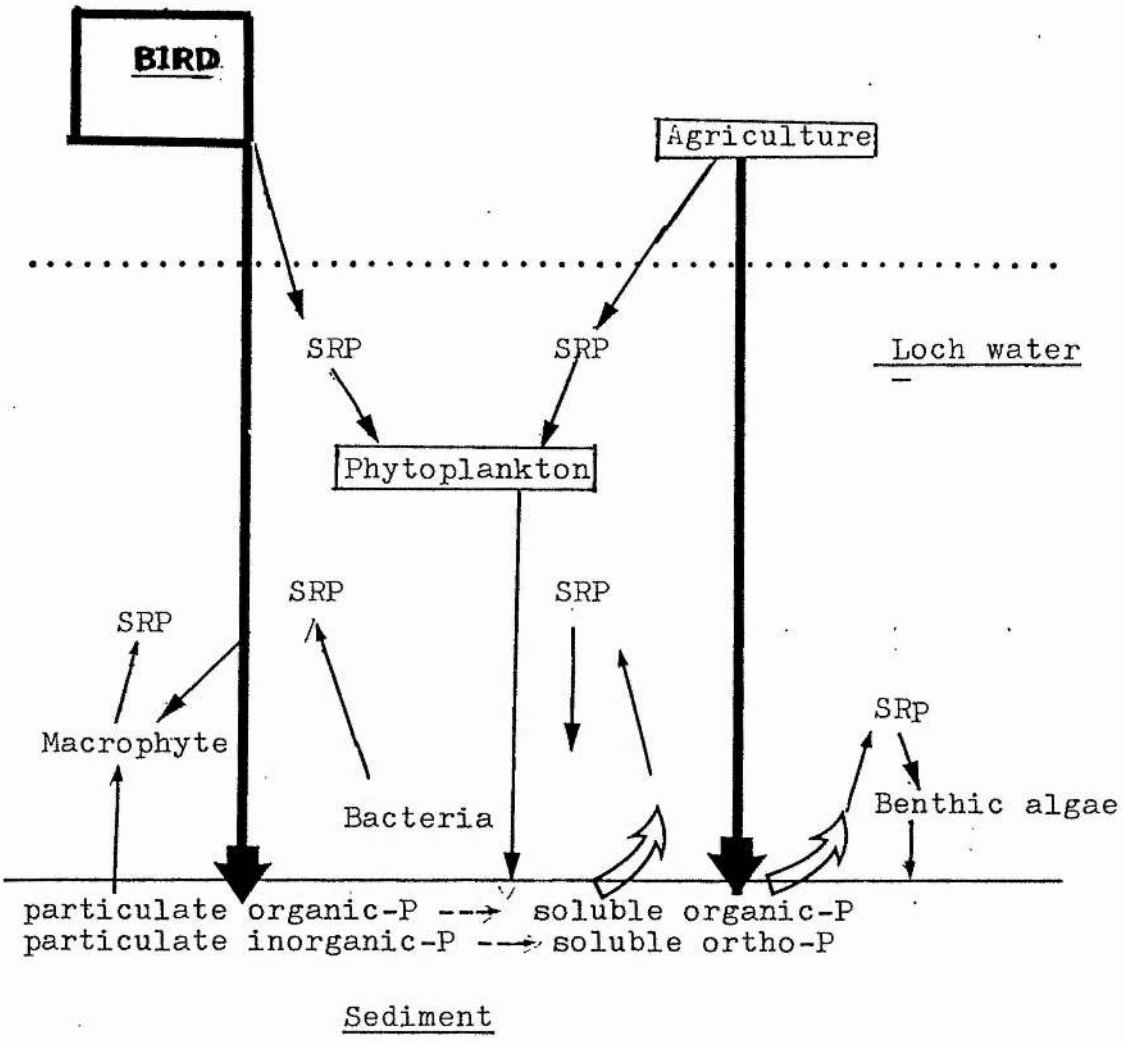

BIRD
Agriculture
SRP
SRP
Loch water
Phytoplankton
SRP
SRP
SRP
SRP
Macrophyte
Bacteria
Benthic algae
particulate organic-P ---> soluble organic-P
particulate inorganic-P ---> soluble ortho-P
Sediment

Figure 4:1

SUMMARY

SUMMARY

The high soluble reactive phosphate concentration in the water and also the frequent occurrence of massive algal blooms in warm conditions indicate that Loch Kilconquhar is more eutrophic than Loch Lindores. The following points summarize the results from field work in both lochs and also several experiments conducted in the laboratory.

a) Loch Lindores

1) Although Loch Lindores is considered a eutrophic loch, the soluble phosphate in the loch is low compared with other nutrients (for example nitrate and silica). No nutrient release from the sediment was observed during the study period. This possibly explains why the soluble phosphate in Loch Lindores water was so low.
2) The drainage inflow from the agricultural area has a high nitrate concentration, but a low phosphate concentration.
3) Apart from the massive Anabaena flos-aquae bloom which occurred in early autumn 1979, there were no other blue-green blooms observed in the loch. However, in early spring, the Asterionella formosa was generally high.
4) This loch has few submerged macrophytes, but benthic algae (sedimentary chlorophyll) populations are high.

b) Loch Kilconquhar

1) Loch Kilconquhar is an over-eutrophicated loch as nutrients in the water are high, particularly phosphate,

and blue-green algal blooms are frequent.

2) The types of submerged macrophytes (for example: Zannichellia palustris, Enteromorpha intestinalis and Cladophora fracta) are "cultural enrichment" water plants, indicating the loch is highly enriched.
3) The source of nutrient in this loch is mainly from duck and gull droppings which are reasonably high in phosphate. Nevertheless, the inflow which drains from an agricultural area is also important in bringing nutrients, especially nitrate, to the loch.
4) It was observed that nutrient release from the sediment occurred at least once a year in this loch, particularly during warm conditions.
5) During the nutrient release, the dissolved oxygen concentration was very low.
6) In laboratory experiments, the drop in dissolved oxygen concentration was correlated with the fall in redox potential and at the same time, substantial amounts of nutrients, particularly phosphate, were released into the overlying water.

REFERENCES

REFERENCES

ALLEN, E.D. and SPENCE, D.H.N. (1981). The differential ability of aquatic plants to utilize inorganic carbon in fresh water. New Phytologist, 87, 269-285.

ARMITAGE, E.G. (1974). The run-off of fertilizers from agricultural land and their effects on the natural environment. In: Pollution and the use of chemicals in agriculture (ed. Irvine and Knight), 43-60. Butterworths, London.

American Public Health Association (APHA) (1971). Standard Methods for the examination of water and wastewater. Washington, D.C. (13th Edt.)

BAILEY-WATTS, A.E. (1978). A nine-year study of the phytoplankton of the eutrophic and non-stratification Loch Leven (Kinross, Scotland). Journal of Ecology, 66, 741-771.

BARKO, J.W. and SMART, R.M. (1980). Mobilization of sediment phosphorus by submerged freshwater macrophytes. Freshwater Biology, 10, 229-238.

BAYLEY, I.A.E. and WILLIAMS, W.D. (1973). Inland waters and their Ecology. Longman, Australia.

BELCHER, H. and SWALE, E. (1976). A beginner's guide to Freshwater algae. Natural Environment Research Council.

BINDLOSS, M.E. (1974). Primary Productivity of phytoplankton in Loch Leven, Kinross. Pros. R.S.E. (B), 74, 10, 1972/1973, 157-181.

BIRCH, P.B. and DIMITRIS, E.S. (1981). Nitrogen and Phosphorus recycling in Lake Sammamish, a temperate mesotrophic lake. Hydrobiologia, 80, 129-138.

BLOESCH, J., STADELMANN, P. and BUHRER, H. (1977). Primary production, mineralization and sedimentation in the Euphotic zone of two Swiss lakes. Limnology and Oceanography, V, 22(3), 511-525.

BONOMI, G., GERLETTI, M., INDRI, E. and TONOLLI, L. (1968). Report on Lake Maggiore. In: Eutrophication in lakes and impoundments. (Uppsala Symposium, Sweden) 299-341.

BROOK, A.J. (1964). The phytoplankton of Scottish freshwater lochs. In: Vegetation of Scotland (Edt. Burnett, J.H.) Chpt. 8. Oliver and Boyd, Edinburgh.

BURTON, R. (1977). Ponds: their wildlife and upkeep. David and Charles Co. Ltd.

CARPENTER, S.R. (1980). Enrichment of Lake Wingra, Wisconsin, by submerged macrophyte decay. Ecology, 61 (5), 1145-1155.

CLEGG, J. (1965). Freshwater life. Frederick Warne and Co. Ltd.

COHEN, Y., KRUMBEIN, W.E., GOLDBERG, M. and SHILO, M. (1977). Solar Lake (Sinai) 1. Physical and Chemical Limnology. Limnology and Oceanography, V, 22 (4), 597-608.

COOKE, G.W. and WILLIAMS, R.J.B. (1970). Losses of nitrogen and phosphorus from agricultural land. Water Treatment and Examination, 1993, 253-276.

DOWNEY, W.K. (1977). Lake pollution due to eutrophication definition of problem. In: Lake pollution prevention by eutrophication control. (National Science Council, May 10-11, Ireland), 7-12.

EDINGTON, J.M. and EDINGTON, M.A. (1977). Ecology and environmental planning. Chapman and Hall, London.

FRANKE, R.G. and FRANKE, D.N. (1975). Man and the changing environment. Holt, Rinehared and Winston Press.

GARDARSSON, A. (1979). Waterfowl populations of Lake Myvatn and recent changes in numbers and food habits. Oikos, 23, 250-270.

GIDDINGS, J.C. (1973). Chemistry, Man and Environmental Change, 227-329.

GOLTERMAN, H.L. (1977). Natural and cultural Eutrophication and the OECD programme. National Science Council, Ireland, May 10-11, 11-20.

GOODNERS, J. (1974). Where to Watch Birds. Book Club Ass., London.

GORHAM, E. (1960). Chlorophyll derivatives in surface muds from the English lakes. Limnology and Oceanography, 29-33.

GREGOR, D.J. and JOHNSON, M.G. (1979). Non point source phosphorus imputs of the Great Lakes. In: Phosphorus Management Strategies for Lakes (edt. Loehr, R.C., Martin C.S. and Rast, W.). Ann. Arbor. Science Publishers Inc., 37-59.

GUPPY, S.F. and WOOD, D.G.E. (1978). Chemistry of sediments from two linked lakes in North Wales. Freshwater Biology, 8, 401-413.

GYMER, R.G. (1973). Chemistry of an Ecological approach. Harper and Row Pub.

HARRIMAN, R. (1978). Nutrient leaching from fertilized forest watersheds in Scotland. Joul. App. Eco., 15, 933-942.

HART, B.T., McGREGOR, R.J. and PERRIMAN, W.S. (1976). Nutrient Status of the Sediment in Lake Mulwala 1. Total Phosphate. Aust. J. Mar. Freshwater Res., 27, 129-135.

HARWOOD, J.E., STEENDEREN, R.A.V. and KUHN, A.L. (1969). A quick method for orthophosphate analysis at high concentrations in water. Water Research, 3, 417-423.

HASLER, A.D. and INGERSOLL, B. (1970). Dwindling lake In: Eco-crisis (Edt. Johnson, C.E.). John Wiley and Sons Inc.

HAYER, F.R., REID, B.L. and CAMERON, M.L. (1958). Lake water and sediment, II Oxidation-Reduction relations at mud-water interface. Limnology and Oceanography, 308-317.

HOLDEN, A.V. and CAINES, L.A. (1974). Nutrient Chemistry of Loch Leven, Kinross. Proc. R.S.E. (B), 74, 7, 1972/73, 101-121.

HORNE, A.J. (1979). Nitrogen fixation in Clear Lake, diel studies on Anabaena blooms. Limnology and Oceanography, 24(2), 329-341.

HOWES, B.L., HOWARTH, R.W., TEAL, J.M. AND VALIELA, I. (1981). Oxidation-reduction potentials in a salt marsh: spatial patterns and interaction with primary production. Limnology and Oceanography, 26 (2), 350-360.

HUMPHREY, G.F. (1978). The recalculation of marine chlorophyll concentrations with special reference to Australia waters. Aust. J. Mar. Freshwater Res. 409-416.

HUTCHINSON, G.E. (1975). Chemistry of Lakes. In: A treatise on Limnology. Vol. 1, Part 2. John Wiley and Son.

KUCERA, C.L. (1978). The challenge of ecology. C.V. Mosby Company, Saint Louis.

LEAH, R.T., MOSS, B. and FORREST, D.E. (1978). Experiments with large enclosures in a fertile, shallow, brackish lake, Hickling Broad, Norfolk, United Kingdom. Int. Revue ges. Hydrobiol., 63, 291-310.

LEE, R.E. (1980). Phycology. Cambridge University Press.

LEENTVAAR, P. (1966). Observations in Guanotrophic Environment. Rivon, 247, 441-489.

MACKERETH, F.J.H., HERON, J., TALLING, J.F. (1978). Water analysis, some revised methods for Limnologists. Freshwater Biological Association, No. 36.

MAULOOD, B.K. and BONEY, A.D. A seasonal and ecological study of the phytoplankton of Loch Lomond. Hydrobiologia, 71, 239-259.

MASON, C.P. (1965). Ecology of Cladophora in farm ponds. Ecology, 46, 421-429.

MATHIAS, J.A. and BARICA, J. (1980). Factors controlling oxygen depletion in Ice-covered lakes. Canadian Journal of Fisheries and Aquatic Sciences, 37, 185-194.

MORTIMER, C.H. (1941-1942). The exchange of dissolved substances between mud and water in lakes. Journal of Ecology, 29, 280-329.

MORTIMER, C.H. (1971). Chemical exchanges between sediments and water in the Great Lakes: speculations on probable regulatory mechanisms. Limnology and Oceanography, 16 (2), 387-404.

MOSS, B. (1981). Ecology of Freshwaters. Blackwell Scientific Publication.

MURRAY, J. and PULLAR, L. (1910). Bathymetrical Survey of Scottish Freshwater Lochs, 246-250.

NILSSON, S.G. and NILSSON, I.N. (1978). Breeding bird community densities and species richness in Lakes. Oikos, 31, 214-221.

OLAH, J. (1975). Metalimnion function in shallow lakes. In: Limnology of shallow waters (Edt. Salarki, J. and Ponyi, J.E.). Akademiai Kiado, 149-155.

ORDNANCE SURVEY, Sheet No. 21NE and Sheet No. 40EE (1974). Directory Survey, Southampton.

OSCAR RAVERA (1978). Biological Aspects of Freshwater Pollution. In: Commission of the European Communities (Edt. Ravera, O.). Pergaman Press.

OSWALD, J. and BENEMANN, J.R. (1977). A critical analysis of bioconversion with microalgae. In: Biological Solar Energy (Edt. Mitsui, A., Miyachi, S., Pietro, A.S. and Tamura, S.). Academic Press.

PALMER, C.M. (1980). Algae and World Pollution, Chpt. VII. In: Algae and Eutrophication. Castle House Publications Ltd.

PARKER, R.E. (1979). Introductory Statics for Biology. The Institute of Biology's Studies in Biology No. 43. Edward Arnold, 7-26.

PAULIK, G.J. (1971). Anchovies, Birds and Fishermen in the Peru current. In: Environment, Resources, Pollution and Society (Edt. William, J. and Murdock, V.) 156-185.

PEARSALL, W.H. and MORTIMER, C.H. (1939). Oxidation-reduction potentials in water logged soils, natural waters and muds. Journal of Ecology, 483-501.

PELIKAN, J., HADEC, K. and STASTRAY, K. (1978). Pond Littoral Ecosystem. In: Quantitative Ecosystem Research in Czechoslovakian IPB Wetland Project. (Edt. Dykyjova D. and Kvet, J.). Heidelberg, New York.

PROCTOR, V.W. (1962). Viability of Chara oospores taken from migratory water birds. Ecology, 43, 528-529.

REYNOLDS, C.S. and WALSBY, A.E. (1975). Water-blooms. Biol. Rev., 50, 437-481.

RICKEY, J.E. (1979). Patterns of phosphorus supply and utilization in Lake Washington and Findley Lake. Limnology and Oceanography, 24 (5), 906-916.

ROCKWELL, D.C., MARION, C.V., PALMER, M.F., DeVAULT, D.S. and BOWDEN, R.J. (1980). Environmental Trends in Lake Michigan, Chpt. 5. In: Phosphorus Management Strategies for Lakes. 91-132.

ROUND, F.E. (1973). The biology of the algae. Edward Arnold Ltd.

SCHINDLER, D.W. (1978). Factors regulating phytoplankton production and standing crop in the world's freshwaters. Limnology and Oceanography, 478-486.

SLATER, S.J.E. and BOAG, A.J. The phosphorus status of three Eutrophic lakes in Victoria. Aust. J. Mar. Freshwater Res., 29, 263-274.

SKOOG and WEST (1970). Fundamentals of Analytical Chemistry. Butler and Tunner, Ltd., London.

SOLORZANO, L. (1969). Determination of Ammonia in natural waters by the phenolhypochlorite method. Limnology and Oceanography, 799-805.

SOLORZANO, L. (1978). Soluble Fractions of phosphorus compounds and alkaline phosphate activity in Loch Creran and Loch Etive, Scotland. J. Exp. Mar. Biol. Ecol., 34, 227-232.

SREENIVASAM (1972). Ecology of blue-green algae in tropical inland waters. In: Taxonomy and Biology of blue-green algae (Ed. Desikachary). Madras, 1972.

SPENCE, D.H.N. (1964). The macrophytic vegetation of Freshwater lochs, swamps and associated fens. (ed. J.H. Burnett), 306-425. Oliver and Boyd, Edinburgh.

SPENCE, D.H.N. (1981). The zonation of plants in freshwater lakes. Adv. Ecol. Res. (in press).

STRAHLER, A.N. and STRAHLER, A.R. (1974). Introduction to Environmental Science., Hamilton Pub. Comp., California.

THOMANN, R.V. and SEGNA, J.S. (1980). Dynamic phytoplankton - phosphorus model of lake Ontario. Ann. Arbor. Science Publishers Inc.

VALLENTYNE, J.R. (1955). Sedimentary chlorophyll determination as a paleobotanical method. Canada Journal Bot., 35, 304-313.

VALLENTYNE, J.R. (1974). The algal bowl lakes and man. Mis. Special Pub. 22, Ottawa.

VAMOS, R. and TASNADI, R. (1975). Soda and H_2S formation in alkali lakes. Sym. Biol. Hung., 15, 189-193.

VERNON, J.D.R. (1972). Feeding habitata and food of black-headed and common gulls. The Journal of British Trust for Ornithology, 19, 18-29.

VINER, A.B. (1975). The sediments of lake George (Uganda). 1. Redox potential. Arch. Hydrobiol., 76, 181-197.

VOLLENWEIDER, R.A. (1974). A Manual on Methods for measuring primary production in aquatic environment. IPB, 1974.

VOLLENWEIDER, R.A. (1970). Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference of nitrogen and phosphorus as factors in eutrophication. OFECD - Sept. 1970, Paris.

WARD, B. and DUBOS, R. (1980). Only one earth. Penguin Books.

WEST, G.S. and FRITSCH, F.E. (1968). A Treatise on the British Freshwater algae. Bibliotheca Phycologica. Wheldom and Wesley, Ltd., New York.

WESTLAKE, D.F. (1974). Macrophyte. In: A Manual on methods for measuring primary production in Aquatic Enviroments (ed. Vollenweider, R.A.). IPB, 1974.

WHITFORD, L.A. and SCHUMACHER, G.J. (1973). A Manual of freshwater algae. Pub. by Sparks Press.

WELCH, E.B., PERKINS, M.A., LYNCH, D. and HUFSCHMIDT, P. (1979). Internal phosphorus related to rooted macrophytes in a shallow lake. Proc. of Conference at Madison, Wisconsin (Ed. Breck and Prentki). Wisconsin.

APPENDICES

APPENDIX I

Redox potential

Oxygen dissolved in water generates a redox potential at a bright platinum electrode according to the reaction

$$O_2 + 2H_2O + 4e = 4OH^- \qquad - \quad (1)$$

If the reaction were to take place reversibly, the redox potential E_h, set up at such an electrode would be given by

$$E_h = E_o - \frac{RT}{F} \ln \frac{a_{OH^-}}{\sqrt[4]{P_o}} \qquad - \quad (2)$$

where E_o can be obtained from thermodynamic considerations, as is explained by Cooper, and where a_{OH^-} is the activity of hydroxyl ions and P_o the partial pressure of oxygen. Since the activity of hydroxyl ions depends on pH, or more accurately the activity of hydrogen ions,

$$- \log a_{OH} = pKw - pH \qquad - \quad (3)$$

(Hutchinson, 1975)

APPENDIX II

Statistical Analysis of the Data

x = Observed measurement

n = Numbers of sample

$\bar{x}$ = Mean

s^2 = Estimated variance

s = Standard Deviation

t = Student's t

f = Numbers of degrees of freedom.

1. Calculation of Standard Deviation and Range for the Mean at the 95% confidence level when the number of samples is small.

Standard Deviation is calculated by substituting in the following

$$s = \left(\frac{\sum x^2 - \frac{(\sum x)^2}{N}}{N - 1} \right) \qquad - (1)$$

From this the Range is calculated by substituting in the following

$$\bar{x} + \frac{ts}{\sqrt{n}} \text{ to } \bar{x} - \frac{ts}{\sqrt{n}} \qquad - (2)$$

t is taken at 95% confidence level.

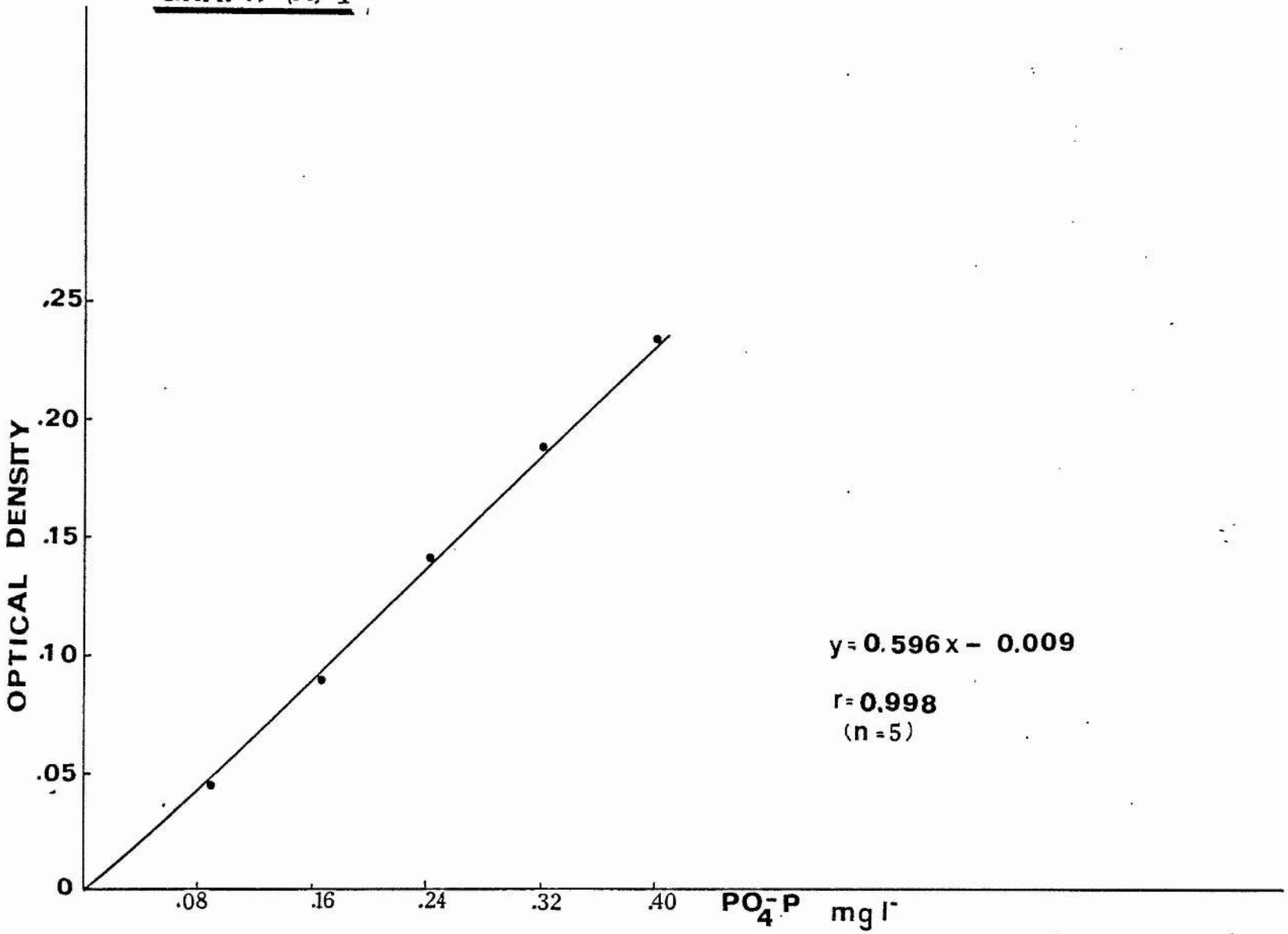
(Parker, 1979)

GRAPH (A) I

(opposite)

Standard curve for phosphate using the modified Harwood, Steenderen and Kuhn technique; micrograms of phosphate plotted against optical density.

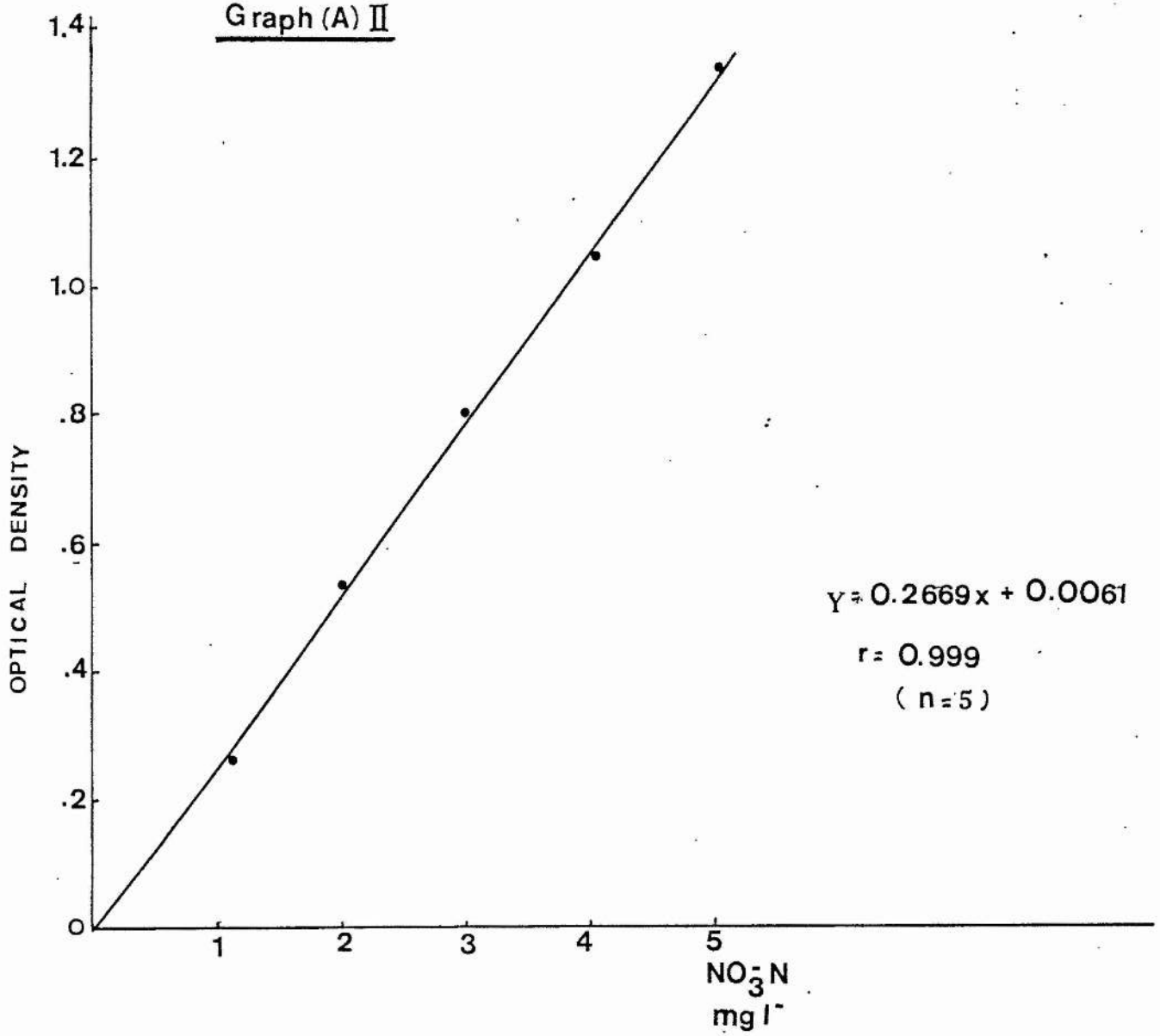
GRAPH (A) I


OPTICAL DENSITY
.25
.20
.15
.10
.05
0
.08
.16
.24
.32
.40
PO_4^-P mg l^-
y = 0.596 x – 0.009
r = 0.998
(n = 5)

GRAPH (A) II

(opposite)

Standard curve for nitrate using American Public Health Association technique; micrograms of nitrate plotted against optical density.

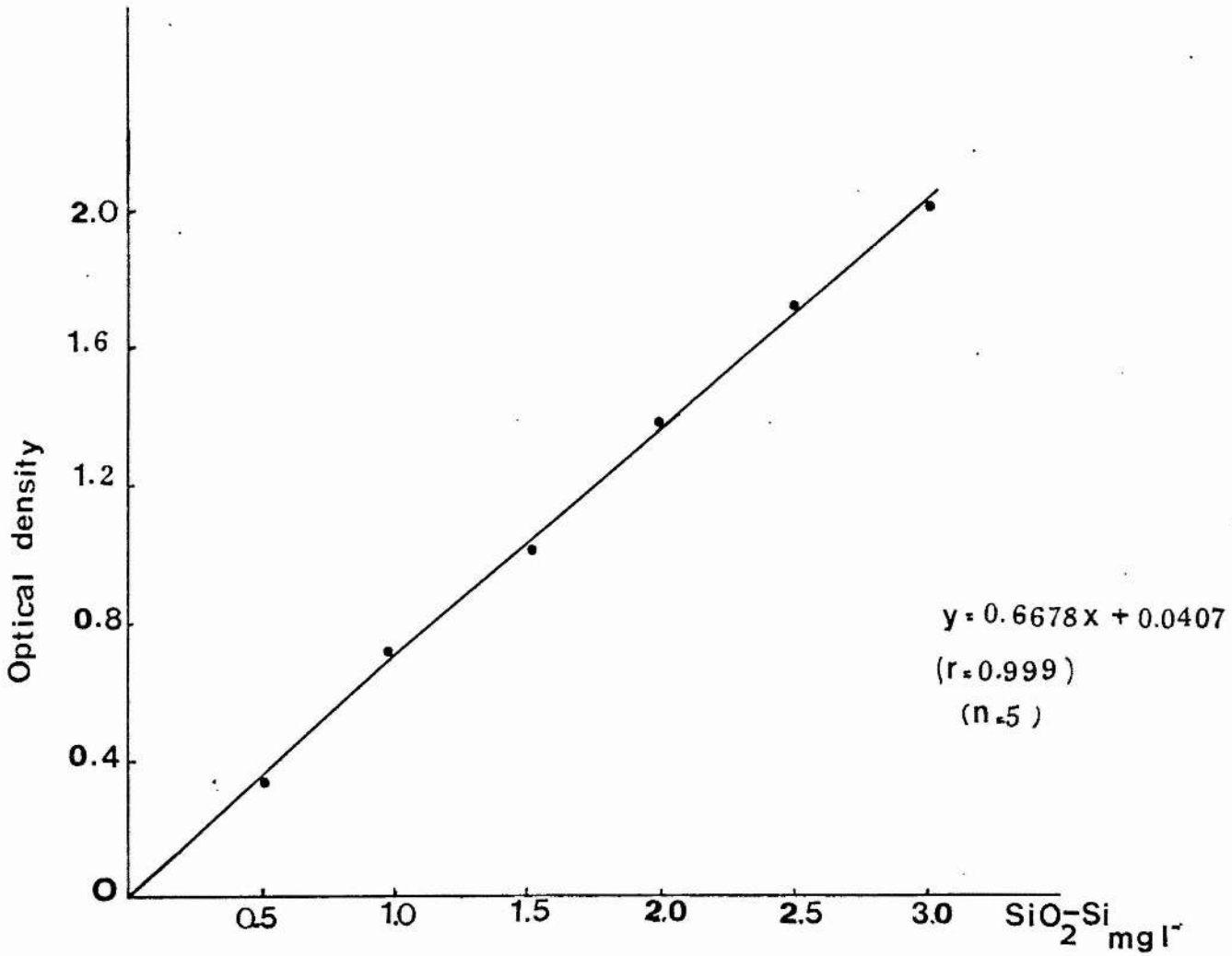

Graph (A) II
1.4
1.2
1.0
.8
.6
.4
.2
0
OPTICAL DENSITY
1
2
3
4
5
NO_3^-N
mg l^-
Y = 0.2669 x + 0.0061
r = 0.999
(n = 5)

GRAPH (A) III

(opposite)

Standard curve for silica using the modified Mackereth, Heron and Talling technique; micrograms of silica plotted against optical density.

Graph (A) III


Optical density
2.0
1.6
1.2
0.8
0.4
0
0.5
1.0
1.5
2.0
2.5
3.0
SiO_2-Si mg l^{-1}
y = 0.6678x + 0.0407
(r = 0.999)
(n = 5)